

Locking systems

Task and design

The locking system of a vehicle includes all those components that facilitate authorized access to and exit from the vehicle. These components also prevent the inadvertent opening of doors, gates, and lids and unauthorized entry. The tasks they must perform are as follows:

- facilitating vehicle access (e.g., via the side doors) to all authorized persons and access to the interior (e.g., via engine hood, luggage compartment, glove compartment, or fuel filler cap),
- facilitating the opening of doors from the inside and outside,
- protecting occupants against inadvertent door opening,
- keeping doors, gates, and lids securely closed during vehicle operation and in crash situations and immobilizing,
- protecting the vehicle against theft when the vehicle is parked,
- detecting an opened or closed door.

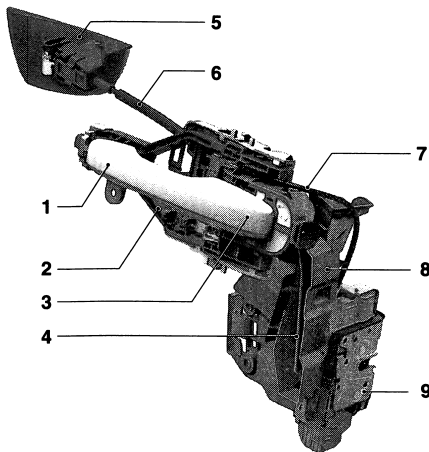
- identification system (mechanical key, remote key, Near Field Communication via chip in the remote key or smart phone),
- outer control (mechanical pull or flipper-type handle, pushbutton or proximity-type sensor),
- outer locking (mechanical lock barrel, pushbutton or proximity-type sensor),
- inner locking (mechanical pull handle, pushbutton or proximity-type sensor),
- inner locking (mechanical control, pushbutton or proximity-type sensor),
- lock (mechanical, mechanical-electric, electric),
- lock holder,
- connecting elements (rods, Bowden cables, electrical leads),
- door, gate, and lid drives,
- ECU (door ECU or central ECU).

The further types refer to the locking system in the side door, since it combines the most functions and the greatest complexity.

The locking system can consist of the following components (Figure 1):

Figure 1: Components of the locking system in a vehicle side door

- 1 Outer handle,
- 2 Outer-handle plate,
- 3 Lock barrel
(behind the cover plate),
- 4 Outer-locking rod,
- 5 Inner handle,
- 6 Bowden cable for inner handle,
- 7 Bowden cable for outer handle,
- 8 Retaining bracket,
- 9 Side-door lock.



Access authorization

Standard

Today's standard is represented by remote keys, which at the touch of a button by the user send a coded data packet at a UHF frequency (433 MHz or 868 MHz) to the vehicle. This data packet changes with each actuation in order to prevent "eavesdropping" (see Immobilizer). These data packets typically consists of a fixed-code part and a rolling-code part which are generated according to an algorithm. The receiver decrypts this code with the same algorithm and thereby identifies permissible combinations. Each code can only be used once. Once the received data packet is identified as permissible, the locks are electrically unlocked and the vehicle owner can open the doors by pulling on the outer control. The mechanical key now only acts as an emergency actuator in the event of a remote-key malfunction or a power failure.

Keyless entry

So-called passive-entry or keyless-entry access systems are becoming increasingly popular. These do not require any electrical-unlocking action by the vehicle owner. It is enough for the owner to be carrying the ID transmitter about their person. A chip inserted in the remote key or a suitable smart phone can serve as the ID transmitter (Near Field Communication). With these systems the opening request is

automatically detected by the vehicle – for instance when approaching a capacitive sensor in the outer door handle, when pulling on the outer door handle, or when operating a pushbutton in the handle. The central ECU in the vehicle sends a signal at a low frequency (125 kHz with a range of around one meter) to the chip in the ID transmitter. The latter reacts to a UHF frequency with a range of up to 20 meters and sends back a coded reply sequence to the vehicle. Access is authorized and the doors are unlocked.

The opening speed is crucial to the user's comfort and convenience. Both the response time of the identification protocol and the unlocking of the doors must be so short that there is no waiting time. The user should not have to pull repeatedly on the outer door handle before the door opens.

In a passive-entry system the reply sequence also changes with each request so as to prevent "eavesdropping". However, a security risk is posed by so-called "relay-station attacks". In such attacks the range of the signals of vehicle and ID transmitter are extended with portable transmit/receive stations. One of these devices must be close to the vehicle to be able to receive and boost the low-frequency signal. In this way, the ID transmitter can also be scanned unnoticed by the user over large distances and the vehicle unlocked or started. In newer systems the passive-entry function can be deactivated to prevent such manipulations.

Lock design

Locking mechanism and lock holder interaction

The locking mechanism (Figure 2) in the lock establishes a separable connection with the lock holder mounted on the body. Indirectly locking systems have gained acceptance on the market. The holding-closed and locking functions are split between two components – the spagnolet (holding closed) and the locking pawl (locking). The lock holder is enclosed by the spagnolet when the door is closed. The spagnolet is driven by the lock holder, rotated, and locked in the door opening direction by the spring-loaded locking pawl. These indirect systems require only minimal opening forces.

During the closing operation the locking mechanism must be able to compensate door tolerances in relation to the body. The position of the door in the closing direction is determined by the lock holder. This is adjusted once during vehicle assembly in order to set the door alignment and the gap dimensions.

Preliminary detent and primary detent

Statutory requirements such as two-detent capability, tensile values, and 30-g strength must be satisfied when it comes to locking-mechanism design. Two-detent capability means that the spagnolet can be held in two positions by the locking pawl – the preliminary and the primary detent. In the primary detent the door is in the desired closing position, i.e., flush with the body, and the door seals are fully compressed. The preliminary detent is a position roughly 5 to 7 mm before the primary detent; in this case the door is not fully closed and the door seals are only partly compressed. In this position watertightness is not guaranteed and driving noises can be clearly heard.

The preliminary detent fulfills two main functions: If the lock inadvertently leaves the primary-detent position, the door is caught again and does not swing open. If the swing is too small when closing, the door remains at least in the preliminary detent and cannot open again inadvertently. Premium locks with an electric closing aid go a step further: They move the door with the aid of an additional motor automatically from the preliminary to the primary detent, slamming the door shut is no longer necessary.

Opening chain

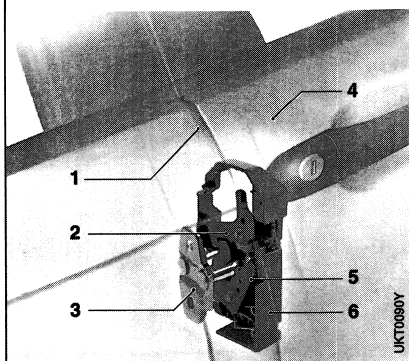
To open the door, the locking of the spagnolet by the locking pawl must be removed. The system here is strained by the pressure of the compressed door seals. The locking pawl is connected with the door handles via a lever chain of connecting elements such as rods or Bowden cables. This is also known as the opening chain, which transfers the handle travel up to the locking pawl. The action of swinging out the locking pawl disengages the tension generated by the seal pressure, the door is released, and the typical opening sound can be heard.

Aside from the pull (Figure 3) and flipper-type variants, the outer handle can also feature pushbuttons or proximity-type sensors. This provides solutions in the lock in which a motor lifts out the locking pawl and thereby opens the lock. This is already standard in rear locks.

To control entry and exit one or more switchable couplings are required in the

Figure 2: Sectional view of a typical locking mechanism with lock holder

- 1 B-pillar,
- 2 Locking pawl (in the door),
- 3 Lock holder (in the B-pillar),
- 4 Front passenger door,
- 5 Spagnolet,
- 6 Lock housing.



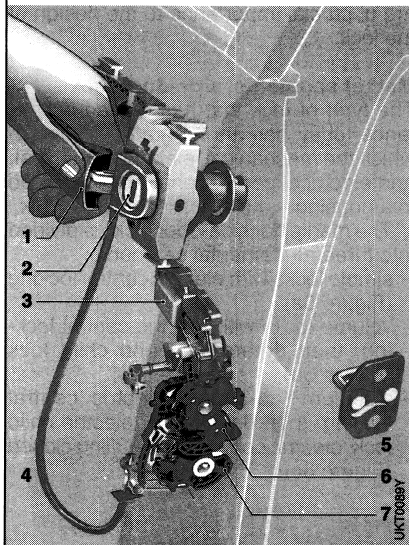
lock which interrupt the opening chain for the outer or inner handle. The door is then locked.

Outer locking

Most of today's vehicles have a central-locking system, which is activated from the outside via the remote key. If the vehicle is without electric power and hence the central-locking system is no longer working, a mechanical lock barrel usually mounted on the driver's door in the outer handle (often under a protective cap) enables the vehicle to be manually locked and unlocked. This is also the case for vehicles with mechanical locks, i.e., without central locking. Vehicles with the passive-entry function as a rule incorporate another pushbutton or a sensor surface in the outer handle which must be actuated to lock the vehicle.

Figure 3: Opening chain for the outer control

- 1 Outer door handle, 2 Lock barrel,
- 3 Central-locking motor,
- 4 Bowden cable for outer handle,
- 5 Lock holder in the B-pillar (striker),
- 6 Spagnolet, 7 Locking pawl.



Inner locking

The inner locking, the "knob" in the inside door panel, has already been dropped by some manufacturers. It is replaced in part by an LED in the driver's door in combination with an electric pushbutton in the dashboard or the door and an emergency-locking facility on the lock. This emergency-locking facility enables the vehicle to be locked even when it is without electric power and protected against theft if the battery is flat. The locking action is then performed by means of a lever on the front of the door; this must be opened for operation purposes. Sensor surfaces on the inside of the door or gesture control to activate the central locking from the inside are also conceivable future developments.

Central locking via DC motor

The couplings can be switched either manually by the outer and inner locking or by a DC motor incorporated in the lock (Figure 4). The latter is the case in a central-locking system. In this case all four doors and the rear lock are electrically locked simultaneously. The locking function can be manually canceled by pulling the inside door handle once or twice. The electric central locking is activated via the radio remote control and a passenger-compartment button, for example in the dashboard.

Child-lock function

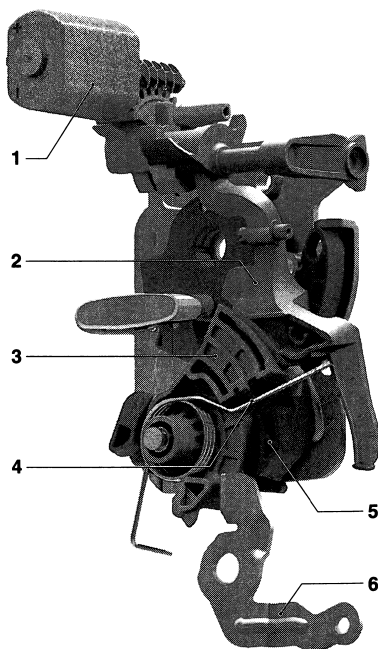
The child-lock function for the rear doors is a special feature. This function merely disengages the inner handle, preventing rear occupants from being able to open the rear doors from the inside. Depending on the lock used, the door can however be unlocked (but not opened) from the inside, enabling persons outside the locked vehicle to gain entry. The child lock can be activated manually or by a motor in the lock. This is done manually by means of a lever which can be accessed only when the door is open.

Requirements

A side-door lock is subject to an extensive range of requirements. Aside from the legal requirements FMVSS 206 [1] and ECE R11 [2], each manufacturer specifies its own statement of requirements which extends far beyond the statutory provisions. Table 1 provides an overview of the essential requirements relating to a side-door lock as typically apply today.

Figure 4: Typical couplings in the outer and inner opening chain of a side-door lock

- 1 Motor for central locking,
- 2 Locking lever,
- 3 Release lever,
- 4 Coupling spring
(unlocked in pictured position),
- 5 Locking pawl,
- 6 Outer-control lever.



Lock layout

The primary concern when it comes to the layout and design of the lock as a safety component is functional robustness. This is followed by criteria such as haptics and acoustics. This involves a pleasant operating feel and a closing and actuator noise that is to impart a high-quality look and feel. Depending on the functional equipment, a side-door lock can consist of 30 to 100 individual parts which interact with each other.

The tensile values or tensile strength of a locking system describe the forces that the locking system must withstand without disengaging. Resilient elements – e.g., elastomer buffers – are required in the lock to prevent door movement and associated noises during vehicle operation. This ensures good closability on the part of the door and the best possible immobilization. The buffers serve to reduce the energy of the swing motion when the door is closed.

During vehicle operation relative movements between the door and the body and consequently also between the lock holder and the lock occur. These can cause noises such as cracking or creaking on account of stick-slip effects particularly in the event of contamination by dust. Material pairings, contact geometries, the rigidity of the lock, and protection against dust accumulation are of crucial importance to the design of the lock.

Market segments, side-door locks

The type of lock that has gained acceptance today has an integrated design in which the mechanical, electromechanical, and electrical components are integrated in a housing – the so-called system lock.

The market for side-door locks is divided into three fundamental segments:

- simple locks with electric central locking (Figure 5a),
- volume locks with electric central locking, theft deterrence, and child lock (Figure 5b),
- premium locks with electric central locking, theft deterrence, electric child lock, electric opening and pulling closed (Figure 5c).

Manufacture

A lock is made up of stampings, injection-molded plastic parts, cold-upsetting parts, springs, sensors, and DC motors. They are manufactured using a variety of production techniques such as riveting, screwing, gluing, and laser welding.

Functional robustness

Functional robustness is verified as standard by means of test catalogs harmonized with the vehicle manufacturer. These are based on the requirements set out in Table 1 and are conducted on test equipment in laboratories. The vehicle manufacturer

often conducts its own tests in vehicles as well.

Validation

Real tests cannot take into account all the influencing factors that occur during series production over a number of years and millions of products. These include for example geometric tolerances of individual parts or deviations from material characteristic values. This can only be delivered by simulation calculations since many factors can be taken into account here with justifiable expenditure.

Table 1: Typical requirements with regard to a side-door lock

Temperature range	– Continuous operation: -40°C to $+80^{\circ}\text{C}$ – Refinishing: 120°C, 1 hour – Extreme load: 300°C, 2 minutes
Number of door closings	– 100,000 cycles
Number of electric lockings (central locking)	– 60,000 cycles
Tensile forces	– 9 kN in primary detent longitudinal acc. to FMVSS 206 – 8 kN in primary detent transverse acc. to FMVSS 206 – Requirement of the original-equipment manufacturers (OEM) is today double FMVSS 206 and higher
Environmental requirements	– Functional robustness against water, dust and various liquids in all temperature ranges including cyclic repetition with freezing – Corrosion requirements: 144 to 720 h in salt spray
Control forces and control travel at the lock	– As a rule specification of the control forces before and after continuous running for a defined door-seal pressure (100 to 300 N) and control speed at the lock (100 to 300 mm/min); typically 15 to 20 N – Opening capability after an accident up to 5000 N tension
Acoustics	– No rattling or creaking noises – Pleasant closing and actuator noises
Push-in forces	– Force to press the lock holder into the primary-detent position: as a rule under 50 N
Electrical requirements	– Operating voltage 9 to 16 V, start assistance 24 V – Max. permissible current ≈ 5 to 8 A – Control times for central locking, theft deterrence, electric child lock 50 to 500 ms – Actuating forces for central locking with inner-locking knob: 8 N – Cut-off-voltage peaks: -75 V to $+150\text{ V}$ – Electromagnetic compatibility as per EMV3 acc. to CISPR 25 [3]
Acceleration resistance	– Centrifuge test with 30 g stationary acceleration – Sled test with acceleration profile
Extreme requirements (misuse)	– Under other drop tests, up to 10 to 15 times increased control forces, up to 1000 mm/s increased control speeds

Based on the typical requirements as set out in Table 1 the following are used for the purpose of design and layout:

- virtual strength and structure tests using the finite-element method (FEM, Figure 6),
- virtual functional tests based on multiple-body simulation (MBS),
- statistical tolerance calculations based on the Monte Carlo method.

Simulation calculations are also carried out for the progression of the control forces in order to achieve good lock haptics. The effectiveness of design optimizations can thus be easily verified. In the case depicted in Figure 7 it was possible to reduce the control force from 45.8 N to 36.6 N with the lever ratios and contact points being optimized.

The control-travel figures of the lock with tolerances are crucial to the functionality of the locking system. Here many individual spatial tolerances interact in the control chain and these are superimposed with the aid of statistical calculations, the so-called Monte Carlo method. The result is control-travel figures with the associated tolerances and the probability of their occurrence.

Acoustic simulations are also possible and replace complex measurements at least in part. Optimizations can thus

already be defined in the design phase, significantly reducing complex prototypes and measurements. New software tools today also facilitate flow simulations for the

Figure 6: Comparison of real and simulated tensile test using the finite-element method

- a) Real depiction of the lock,
b) Calculation with finite-element method.

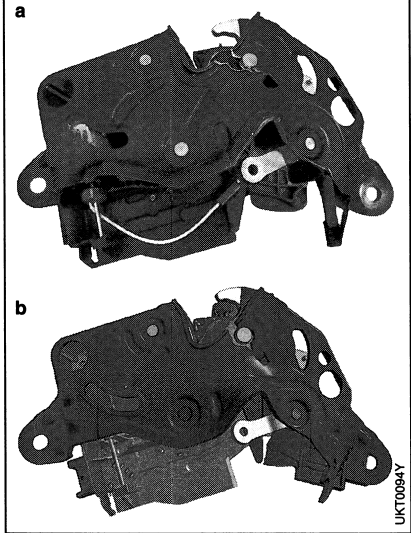
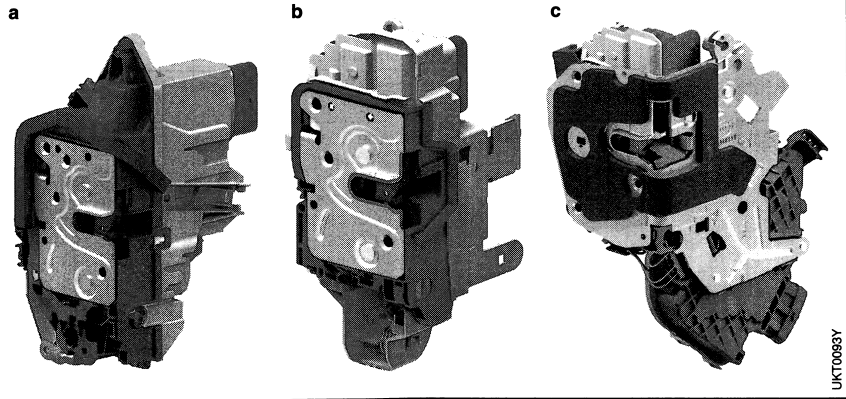


Figure 5: Lock types

- a) Simple lock,
b) Volume lock,
c) Premium lock.



assessment and optimization of dust and water robustness.

In spite of the ever-increasing accuracy of simulation methods and material models, real test still cannot be completely replaced. This applies above all to environmental influences such as dust, water, and freezing and also to specific acoustic effects such as creaking. Realistic laboratory tests are carried out to avoid costly, complex vehicles tests with test drives.

To obtain meaningful tests in the laboratory, the dust must conform to realistic conditions with regard to composition and particle size. The same applies to the density of the dust and the air flow, which must reproduce the conditions in the door as accurately as possible. A dust-accumulation picture as from real test procedures can then be generated in the laboratory with a dust chamber.

Dust and other environmental influences such as dirt also play a role in the previously mentioned phenomenon of creaking. This arises due to friction between the door and the body in the lock – or more exactly by the lock components which are in contact with the lock holder. The occurrence of a creaking noise can be verified in the

laboratory by determining movement profiles and contact forces between the lock and the lock holder and the dirt and dust accumulation in the vehicle. This makes possible design improvements already at a very early stage in the development phase. Figure 8 depicts two design states of a lock. It was possible to eliminate the creaking by introducing furrowing in the contact area of the lock holder with the lock.

Figure 7: Control-force simulation for inner control with optimization loop

- 1 First optimization loop,
- 2 Second optimization loop.

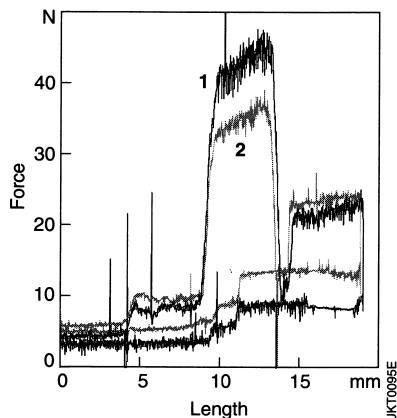
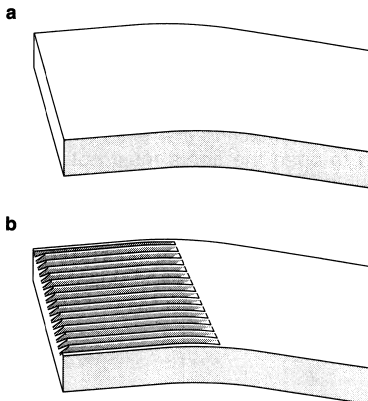


Figure 8: Design measure on the lock holder to reduce the creaking noise

- a) Series state with creaking,
- b) Optimized series state with furrowing (creak-free).



Safety functions

Behavior in a crash

The locking system must keep the doors securely closed during vehicle operation. In a crash situation high accelerations, forces, and deformations occur. These must not lead to the failure of the locking-mechanism/lock-holder connection and the unintended opening of the door. After the collision and in a rescue situation, however, the door should be easy to open. To keep the door closed during a crash, in many cases today mass locking mechanisms are installed in the outer door handles. These consist of a weight that is moved during customary accelerations in the crash and then block the outer door handle. This stops the handle from moving outwards and opening the door.

There are additionally tactilely operating systems. In these systems a lever attached to the lock touches the inside of the door outer panel. When this deforms, it blocks the outer control chain, and the door can then permanently not be opened from the outside. This too prevents unintended opening.

Improved systems have speed-based crash freewheels in the side-door lock. If the outer handle is operated too quickly, the movement comes to nothing and the door remains closed. This also covers crash situations in which acceleration-based systems such as mass locking mechanisms do not work. The door can be opened again after the crash.

Theft deterrence

The complete locking system must be protected against electrical, electronic or mechanical tampering. Mechanical and electrical connecting elements which are used to open the doors must not be accessible from the outside or may only be accessible with difficulty from the outside. Certain locks use magnetically operating Hall-effect sensors. These must be fitted in such a way that magnetic fields from the outside cannot cause unlocking or opening.

Many locks have a theft-deterrence system – also called double lock, dead lock or safe function. Depending on the manufacturer, this system is activated always or for instance by pressing the locking button on the remote control twice. Ordinarily this is not possible when there are persons in the vehicle. The theft-deterrence system prevents manual unlocking and opening by the inside door handle, for example after the side window has been smashed. This function is electrically activated in the lock by an additional motor. In the event of a power failure, the theft-deterrence system can be manually deactivated at least on one door via the lock barrel.

Detection of an opened door

The side-door lock also takes on the important task of signaling an open or closed door to the vehicle. This is done by microswitches in the lock which detect the position of the spagnolet and whether the locking pawl has locked. These signals are evaluated either in the door ECUs or in the car's central electronics. Alternatively, some manufacturers also provide door contact switches outside the lock, but these are less accurate.

This information is used to indicate an opened door or trunk lid in the instrument cluster. These signals are also used for the alarm system, automatic relocking of the doors after a certain period of time in the event of incorrect unlocking, or switching off the cruise control when the door is opened.

Development history

Historical view

The first locks to be used in vehicle doors were based on house locks. These so-called drop-latch locks could not compensate any tolerances, were able to absorb forces only in one direction, and had no preliminary detent. All the components were made of steel, the lever apparatus was not encapsulated, and there were no acoustic damping measures.

From around 1945 onwards this design principle was further developed into the so-called pin lock. This could absorb forces in several directions and had preliminary and primary detents. The locking actions was still performed directly by the drop latch.

In 1955 the first indirectly locking systems were introduced; above all, these reduced the control forces and at the same time improved tensile strength. The first acoustic damping materials reduced rattling noises. From 1960 the indirectly

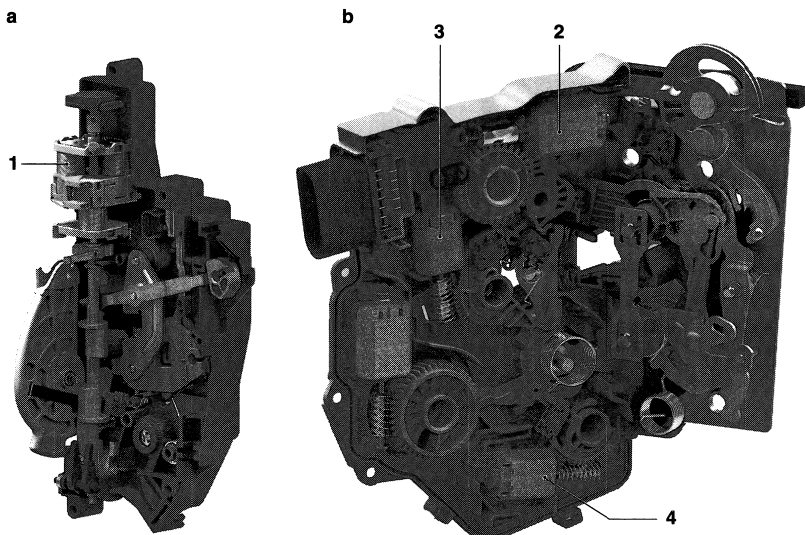
locking systems continued to make inroads into the market. For the most part the spagnolet was on the outside and the lock holder had a more complex design to ensure immobilization with buffer elements. Exclusively mechanical locks were used until the 1970s.

The first locks which locked and unlocked automatically were introduced in the USA in the 1960s. Electromagnets were used to activate them. Pneumatic or electrical control elements (actuators), which were screwed as separate units onto the mechanical basic locks, came later.

The increasing market share of central-locking systems led from the mid-1980s to the actuator being merged with the basic lock, and the so-called system lock was born. Plastic components and sensors were increasingly being used in its design. The indirectly operating locking mechanism with an internal spagnolet became the standard in the ensuing years.

Figure 9: Comparison of a conventional lock with a flex-pole lock

- a) Flex-pole lock,
- b) Conventional lock.
- 1 Flex-pole actuator for central locking, theft deterrence, and electric child lock,
- 2 Motor for central locking,
- 3 Motor for electric theft deterrence,
- 4 Motor for electric child lock.



The first lock modules which brought together the outer and inner handles and the lock into a preassembled and pretested unit came onto the market in the mid-1990s.

Market trends

The mechanical complexity of locking systems increases with rising functionality. This results in increased weight and a variety of versions, both of which should actually be avoided. Possible solutions are reflected in two market trends: Simplifying the lock body by using a flex-pole actuator and simplifying the locking system by using an electric lock.

Today, a separate DC motor is used as a rule for each electromechanical function in a lock. This means – for a lock with central locking, theft deterrence, and electric child lock – the use of three motors. A flex-pole actuator is an electromechanical control element which can perform these three tasks. This eliminates the need for the motors together with the gear units and the

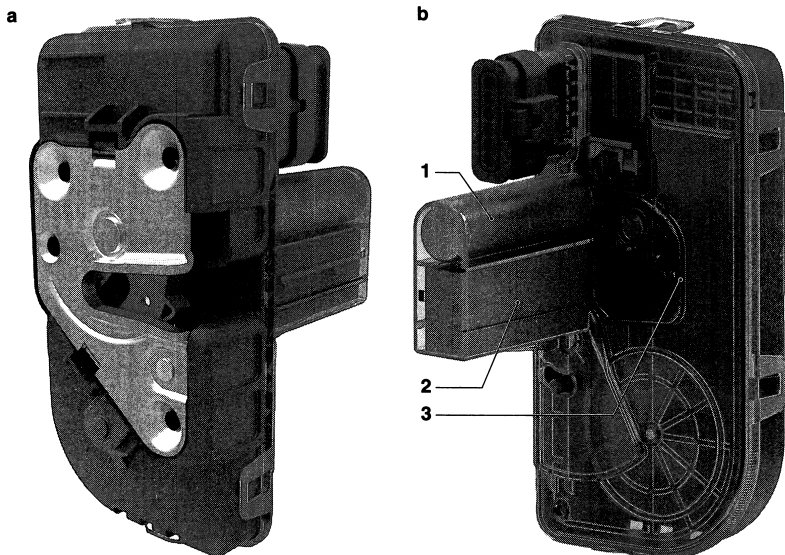
lock becomes lighter, more compact, and more robust. Figure 9 shows a conventional lock and a flex-pole lock in comparison. The interfaces to the handles and control points remain unchanged.

A further simplification is achieved if the conventional interfaces are also dispensed with, for example in the case of an electric lock. Here the locking pawl is lifted out only by an actuator, manual opening is no longer necessary. Sensors, switches or even smart phones can be used as controls. The lock body is also simplified such that the manual interface is dispensed with. Functions like central locking, theft deterrence, and electric child lock are now only effected by the control software.

Figure 10 shows an electric lock with a cable actuator for lifting out the locking pawl. With an electric lock it must be ensured that after a vehicle-battery failure or a power-supply failure it is still possible to open the door. This can be ensured by integrating a redundant voltage source (battery) into the lock.

Figure 10: Electric lock with cable actuator and electrical redundancy

- a) Front view,
- b) Rear view.
- 1 Integrated emergency power supply,
- 2 Integrated control,
- 3 Cable actuator.



References

- [1] FMVSS 206: U.S. Department of Transportation National Highway Traffic Safety Administration, Laboratory Test Procedure for FMVSS No. 206.
Door Locks and Door Retention Components (TP-206-08 February 19, 2010).
- [2] ECE R11: Uniform provisions concerning the approval of vehicles with regard to door latches and door retention components. Addendum 10: Regulation No. 11 Revision 3.
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Anti-theft systems

Once the driver has left the vehicle, the vehicle must be protected against unauthorized use. It must be locked and the windows must be closed. This is expressly determined in the German road traffic regulations (StVO) in §14 s. 2 [1].

According to §38a of the German road traffic licensing regulations (StVZO, [2]) motor vehicles must furthermore be equipped with a security device to protect against unauthorized use. Vehicles are for this purpose equipped with a steering lock (steering-wheel lock), which is for the most part connected to the ignition lock. When the ignition key is removed a bolt is enabled which then engages in a hole in the steering column when the steering wheel is moved. This renders the vehicle unsteerable. When the ignition key is inserted again the bolt is pulled out when the steering wheel is turned and the steering is enabled again.

This does not prevent the engine from being started by short-circuiting the ignition. Protection against this is provided by the electronic vehicle immobilizer.

A car alarm is designed to make stealing a vehicle or breaking into the vehicle difficult by issuing an acoustic and optical alarm.

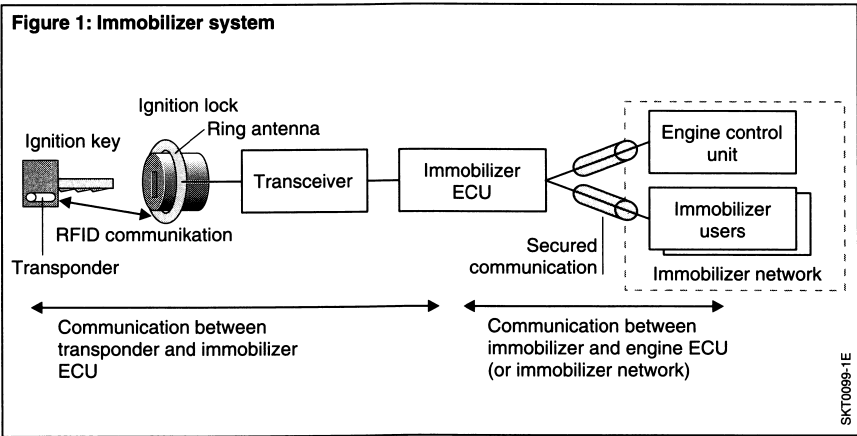
Electronic vehicle immobilizer

The electronic vehicle immobilizer is a theft-deterrence device which is designed to prevent the vehicle from moving under its own power if the associated ignition key is not inserted. Without authentication (checking of an asserted identity) of the transponder integrated in the ignition key, the immobilizer prevents operation of the vehicle by preventing for example engine starting, gear selection, or release of the steering lock.

Since 1998, in accordance with EU Directive 95/56/EU [3], all passenger cars sold in EU countries have been required to be fitted with an electronic immobilizer. Similar regulations apply in many other countries. The electronic immobilizer is not to be confused with automotive alarm systems or with remote-keyless entry systems for remote control of the door locking system.

System design

The electronic immobilizer (Figure 1) is integrated in the vehicle electronics and consists of the following components.



Transponder

The transponder is integrated in the ignition key and consists of an antenna, a microprocessor for signal processing and data transfer, a non-volatile memory (EEPROM) for storing a cryptographic key, and a capacitor as an energy accumulator. Passive RFID transponders (Radio-Frequency Identification) in the long-wave range (125 kHz or 134.2 kHz) are typically used in the automotive industry. These do not have their own energy source and their range is limited to a few centimeters [4].

Transceiver

The transceiver (also called the "reader") is connected to a ring antenna which on account of the short range of the radio signal is located near to or directly on the ignition lock. The transmit/receive unit of the transceiver transmits and receives the radio signals via the antenna and relays them to the immobilizer ECU.

Immobilizer ECU

The immobilizer ECU (also called the immobilizer server) contains a microcontroller for performing the immobilizer-function and communicates both with the transceiver and with the engine ECU, and if necessary with further ECUs in the immobilizer network. The immobilizer function can, instead of being integrated in its own immobilizer ECU, also be integrated in another ECU, e.g., in the instrument cluster, in the on-board computer, or in the engine ECU.

The immobilizer function has the task of checking the authenticity of the ignition key and the transponder and enabling the immobilizer.

Engine ECU

The engine ECU receives the signal to enable the immobilizer from the immobilizer ECU via a cryptographically secured connection. Different switch-off paths are disabled without an active immobilizer enable signal, meaning that engine starting is not possible. Typical switch-off paths are starter, fuel pump, and fuel injection.

Immobilizer network

To enhance security the ECUs of further vehicle components are incorporated into the immobilizer network, e.g., the automatic transmission (gear selection or opening of the parking lock can thus be prevented) or the steering.

Users of the immobilizer network must satisfy heightened security requirements, including securing bus communication and measures to increase protection against manipulation ("hardware security").

Functional description

Communication between transponder and immobilizer ECU

Communication between immobilizer ECU with transceiver and transponder is effected via a radio link and is activated as soon as the ignition key is in range or when the ignition is turned on. The transceiver generates with its antenna an electromagnetic field, which is received by the transponder antenna. Through inductive coupling the transponder receives its energy, which is stored in a capacitor.

Data are transferred as a rule in a half-duplex process: Data from the transceiver to the transponder (downlink) and data from the transponder to the transceiver (uplink) are transferred in succession. The received data are processed by the transponder's IC (integrated circuit). To return data to the transceiver, the transponder does not generate its own electromagnetic field, but instead modulates the transceiver signal by means of load modulation. The transceiver registers the fluctuations and decodes them as a transponder data signal [4].

The aim of this communication is to authenticate the transponder in the ignition key. Here the authentication can be unilateral (only the transponder authenticates itself to the immobilizer) or reciprocal (both the transponder and the immobilizer authenticate themselves to each other).

Authentication is performed in modern immobilizer generations according to the challenge-response scheme (see Figure 2). The prerequisite for this scheme is that the transponder and the immobilizer have a common, secret key K . The immobilizer transmits a challenge to the

transponder, which in turn converts and returns this by means of a cryptographic ENCRYPT function and the secret key K . Then the immobilizer performs the same calculation and compares the results (VERIFY). If the results match, the transponder has successfully authenticated itself to the immobilizer, i.e. proven its authenticity. A random number is typically used as the challenge with the aim of preventing attacks by recording and repeating, so-called replay attacks (see section entitled "Security").

Communication between immobilizer and immobilizer users

The enable signal is transmitted by way of a cryptographically secured communication via the vehicle bus system to the engine ECU and if necessary the other users of the immobilizer network. Once the transponder in the ignition key has been successfully authenticated, the immobilizer is enabled by the immobilizer ECU and normal vehicle operation is possible.

The immobilizer is automatically activated again after the ignition key is removed.

Security considerations

Both older and current generations of immobilizer systems have been successfully attacked in different ways, thereby showing up their weaknesses. Common weaknesses are incorrect implementations, deviations from standardized, cryptographic algorithms and processes, and the use of key lengths that are too short [5], [6], [7]. One requirement that is imposed on an immobilizer system is that the immobilizer even with great criminal application cannot be surmounted or can only be surmounted with great technical effort and financial expense. Attacks should furthermore not be scalable, i.e., knowledge of a successful attack on an individual vehicle should not be reusable for other vehicles. This is achieved among other things by the use of vehicle-individual or component-individual cryptographic keys.

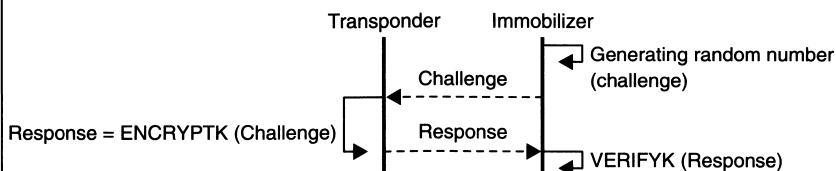
To protect against so-called replay attacks, i.e., eavesdropping on and storing the communication for later use, a new random number (challenge) is generated in the challenge-response scheme for each authentication attempt. A valid authentication message that has been

Figure 2: Challenge-response scheme for transponder authentication

ENCRYPT_K: Encryption with the secret key K .

VERIFY_K: Comparison with internal calculation with the same key K .

Immobilizer is enabled if authentication successful.



eavesdropped on once is thereby rendered invalid for a later authentication attempt and can no longer be used.

Once limitation of the challenge-response protocol shown in Figure 2 is that the transponder cannot check the authenticity of the immobilizer. Figure 3 shows an extension of the existing protocol. The immobilizer generates a random number (challenge) and then calculates its MAC (Message Authentication Code), a checksum for authenticating the challenge. Both the challenge and its MAC are communicated to the transponder. The transponder checks the MAC and can thus ensure that the challenge comes from a known, authenticated immobilizer ECU. Only if the MAC is valid does the transponder proceed with the protocol as described above; otherwise the communication is aborted at this point. This prevents the transponder from reacting to any challenge and sending back the associated response [8].

Production and infrastructure requirements

The use of symmetrical, cryptographic processes imposes heightened requirements on the overall product life cycle of each component relevant to the immobilizer. In production the cryptographic keys must be generated and programmed in a secure environment. Components relevant to the immobilizer are reciprocally paired via their secret key so that when a part is exchanged the associated key must be programmed again and the new components "taught" again.

Further applications are the provision of replacement ignition keys (e.g., after loss) and the disabling of ignition keys after they are stolen. The actions can be authorized by the manufacturer in each case via a central key administration and a secured infrastructure and the secret keys made available.

Figure 3: Challenge-response protocol with reciprocal authentication

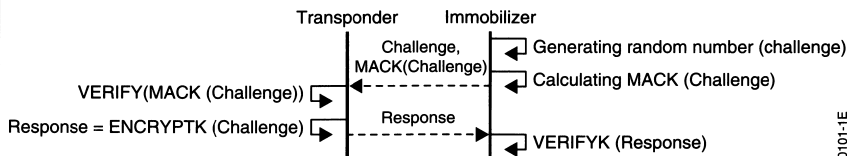
MAC_K (Message Authentication Code): Checksum for authentication.

VERIFY: Comparison with internally calculated checksum.

ENCRYPT_K: Encryption.

VERIFY_K: Comparison with internal calculation.

Immobilizer is enabled if authentication successful.



Theft-alarm system

Regulations

Theft-deterrent (alarm) systems must meet the requirements of ECE regulations R18 [9] and R116 [10]. An armed alarm system must be capable of issuing acoustic and visual alarm signals in the event of unauthorized intervention in the vehicle. Extended requirements result from insurance regulations in various countries.

Permissible alarm signals

- Intermittent sound signals
(25 to 30 s duration, 1,800 to 3,550 Hz; min. 105 dB(A), max. 118 dB(A) at 2 m distance,
- visual flashing signals
(max. 5 minutes).

System design

The alarm system comprises a central control unit, sensors that detect intervention, and an alarm siren (Figure 1).

Alarm detectors

- Door and hood contacts,
- interior monitoring,
- tilt sensor,
- self-monitoring of the alarm siren.

Alarm system control unit

Control of the alarm system is assumed by a control unit of the comfort electrical systems in the vehicle. The alarm system is armed or disarmed via the mechanical locks or via the radio remote control. When the command “Arm” is received, monitoring of the alarm detectors is activated. If required, selection buttons can be used to disable individual sensors. This deactivation applies once to the next “Arm” command.

Alongside the sensors, the alarm siren is also armed. Once the siren has assumed the “Armed” status, the control unit starts cyclical communication to monitor the lines. If an alarm is triggered, deactivation of the alarm (e.g. via the radio remote control) must lead to immediate termination of the alarm.

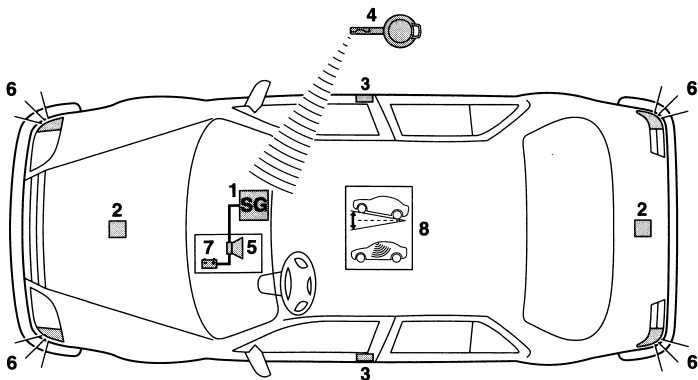
The control unit must ensure that the max. permitted number of alarms per alarm detector is not exceeded. Moreover, overlapping alarms must not lead to prolonged alarm output.

Alarm siren

The alarm siren comprises control-system electronics, a diaphragm as sound source, and a rechargeable battery for redundant power supply. The alarm tone is generated

Figure 1: Theft-deterrent system

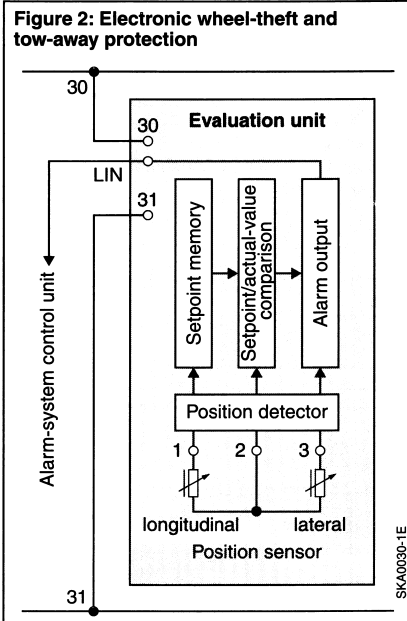
1 Alarm-system ECU, 2 Hood contact, 3 Door contact, 4 Key with radio remote control, 5 Siren, 6 Turn-signal lamps, 7 Battery, 8 Roof module with tilt sensor and interior monitoring.



by, for example, a piezo-loudspeaker. Communication with the control unit of the alarm system takes place across a serial single-wire bus (e.g. LIN). On the basis of a command from the control unit, the alarm siren can trigger the alarm or autonomously detect a manipulation. Here the following signals are monitored: cyclical communication, line contact to terminal 30 and terminal 31, voltage gradient of the vehicle battery, and overvoltage e.g. due to external supply. The aim is to recognize manipulations reliably and to prevent false alarms.

Tilt sensor

The task of the tilt sensor is to detect changes in the vehicle position caused by jacking up or towing the vehicle. A very sensitive acceleration sensor is deployed here. Its signal depends on the angle in relation to gravity. In order to monitor both the longitudinal and transverse axes of the vehicle, twin-axis micro-mechanical sensors are deployed (Figure 2). Particularly important is the reliable prevention of false alarms, as the vehicle rolling, e.g. due to wind, may not lead to an alarm.



Interior monitoring

The reflections of an ultrasound or a microwave field are analyzed. If the modification exceeds a comparative value, the alarm is triggered. Here, too, reliable prevention of false alarms is an important criterion.

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Conventional vehicle electrical systems

Electrical power supply

Function and requirements

The vehicle electrical system of a motor vehicle comprises the alternator as the energy converter, one or more batteries as the energy accumulators, and the electrical equipment as consumers (Figure 1). The energy from the battery is supplied to the starter, which then starts the vehicle engine. During vehicle operation, the ignition and fuel-injection system, the control units, the safety and comfort and convenience electronics, the lighting, and other equipment have to be supplied with power. The alternator supplies the required electrical power for these components and also to charge the battery.

Heightened comfort and safety requirements result in a significant increase in the power demand in the vehicle electrical system. Added to this is the continuing trend towards the electrification of ever more vehicle components (e.g. seat adjustment, electric parking-brake system, electric steering servo). The nominal output of alternators ranges from approx. 1 kW in subcompact-size cars to over 3 kW in the upper class. This is less than the consumers need in total. In other

words, the battery must also supply power at times during vehicle operation.

An equalized battery charge balance must always be guaranteed through the choice and dimensioning of battery, alternator, starter and the other consumers in the electrical system so that the internal-combustion engine can always be started and, when the engine has been switched off, specific electrical consumers can still be operated for an appropriate period of time.

The alternator supplies current (I_G , Figure 1) when the engine is running. To be able to charge the battery, the alternator must increase the vehicle-system voltage above the battery open-circuit voltage. However, the alternator is only able to do this when the cut-in consumers do not demand more current than it can supply. If the equipment current draw I_V in the vehicle electrical system is greater than the alternator current I_G (e.g. when the engine is idling), the battery is discharged. The vehicle system voltage falls to the voltage level of the battery from which current is drawn.

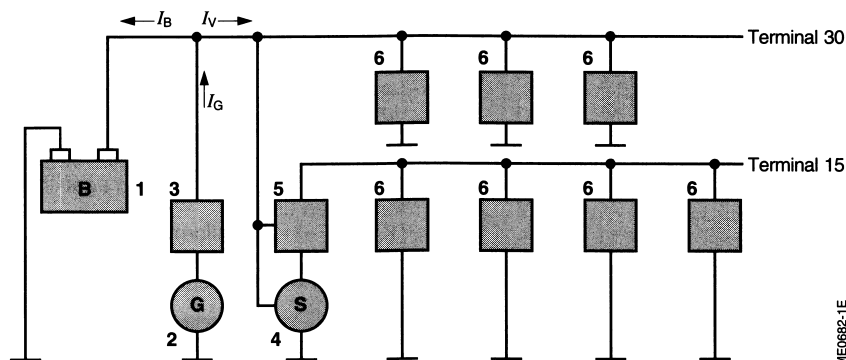
The maximum alternator current is very much dependent on the rotational speed and the alternator temperature. When the

Figure 1: Schematic diagram of a vehicle electrical system

1 Battery, 2 Alternator, 3 Alternator regulator, 4 Starter, 5 Ignition switch, 6 Consumers.

I_B Battery current, I_G Alternator current, I_V Equipment current draw.

B Battery, G Alternator, S Starter.



engine is idling, the alternator can only supply 55 to 65 % of its nominal output. However, immediately after a cold start at low outside temperatures, the alternator is able from medium engine speed to supply the vehicle electrical system with up to 120 % of its nominal output. When the engine is hot, the engine compartment heats up, depending on the outside temperature and engine load, to 60 to 120 °C. High engine-compartment temperatures cause high winding resistances, which reduce the maximum alternator output.

Layout and operating principle of the 14 V electrical system

Schematic diagram

The electric system in a motor vehicle can be represented as the interaction of the energy converter (alternator), the energy accumulator (battery) and the consumers (Figure 1).

The alternator is driven via the V-belt by the crankshaft and converts mechanical energy into electrical energy. The alternator regulator limits the output power such that the desired voltage set in the regulator is not exceeded (14.0 to 14.5 V).

When the ignition key is removed, only a few consumers are supplied with voltage (e.g. anti-theft alarm system, car radio, auxiliary heating). The terminal via which these consumers are supplied is called "terminal 30" (continuous plus).

The other consumers are connected to "terminal 15". When the ignition switch is in the "ignition on" position, the battery voltage is applied to this terminal so that now all the consumers are connected to the power supply.

Battery installation locations

In most cars the battery is located in the engine compartment. However, a large battery (e.g. 100 Ah) takes up a lot of space and sometimes, when the amount of space available in the engine compartment is restricted, may not be able to be installed there. Another argument against installing the battery in the engine compartment is the potentially high ambient temperatures. As an alternative, the battery may be installed in the luggage compartment or in the passenger compartment (e.g. under the front passenger seat).

Effect of installation location on charge voltage

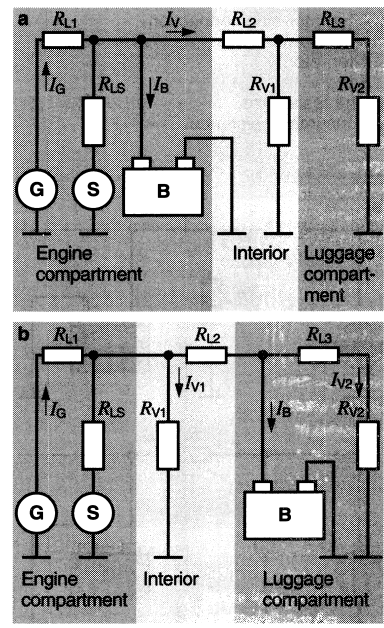
The line between a battery installed in the engine compartment and the alternator is shorter than for a battery installed in the luggage compartment. This affects the line resistance and thus directly the voltage drop on the cable. Voltage drops can be minimized by suitable conductor cross-sections and good connections with low contact resistance, even after a long service life.

Figure 2a shows the conditions for installation in the engine compartment. A battery installed in the luggage compartment requires a longer supply line with the additional line resistance R_{L2} (Figure 2b). Because of the higher voltage drop, the charge voltage for a battery installed in the luggage compartment is

Figure 2: Battery installation locations

- a) Installation in engine compartment,
b) Installation in luggage compartment.

G Alternator, B Battery, S Starter,
 R_L Line resistances,
 R_V Equipment resistances,
 I_G Alternator current,
 I_V Equipment current draw,
 I_B Battery charging current.



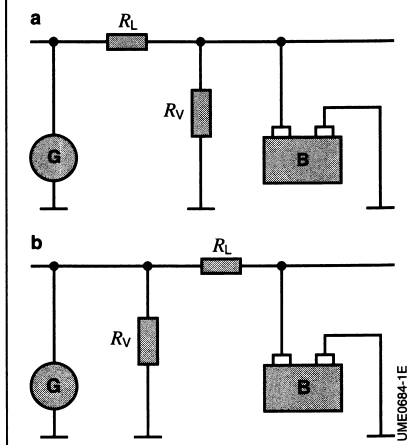
lower. The additional voltage difference caused by R_{L2} can be balanced by increasing the setpoint alternator-voltage value. This increases the alternator output.

Effect of installation location on startability

Startability is dependent on the voltage applied at the starter. The higher this voltage, the higher the starter speed during the starting sequence. Because of the high starter current, the resistance of the supply line has a crucial effect on this voltage. In the case of the variant with the battery installed in the luggage compartment, the line between the battery and the starter is longer than for the battery installed in the engine compartment; accordingly, the resistance and with it the voltage drop are higher. Better startability is assured when the battery is installed in the engine compartment with short lines to the starter.

Figure 3: Connection options for consumers

- a) Battery-side connection of consumers,
 - b) Alternator-side connection of consumers.
- G Alternator,
B Battery,
 R_L Line resistance,
 R_V Consumer resistance.



Effect of ambient temperature

High temperatures, as can be encountered in the engine compartment, intensify aging effects in the battery (e.g. corrosion of the battery and water loss due to gassing), which have a negative impact on battery service life. High temperatures in the battery can be reduced by shielding.

The charge acceptance of the batteries is restricted at low battery temperatures, i.e. the battery takes in less charge, which can lead to a low state of charge. Low states of charge in turn facilitate aging effects such as sulfating, which lead to reduced usable capacity and therefore shorter service life.

Effect of installation location on voltage stability

Because the battery can only be charged with direct current, the alternating current generated in the alternator must be rectified. This job is performed by a diode rectifier integrated in the alternator. Rectification of the alternating voltage creates a pulsating direct voltage. Furthermore, the switching of the diodes – when the current is commutated from one diode to the next – generates high-frequency voltage oscillations, which are smoothed to the greatest possible extent by the interference-suppression capacitor installed in the alternator.

Electronic consumers (e.g. ECUs) can be disrupted or even damaged by the voltage peaks or the voltage ripple. The battery can use its large capacity to smooth the voltage fluctuations. However, because of the line resistance R_L between the alternator and the battery (Figure 3), they are not completely suppressed at the alternator. When the consumers are connected on the battery side (Figure 3a) or after the battery (e.g. R_{V1} and R_{V2} in Figure 2a), they are supplied with the extensively smoothed system voltage. When the consumers are connected on the alternator side, i.e. directly to the alternator (Figure 3b), they are exposed to a greater voltage ripple and greater voltage peaks.

Electrical devices (consumers) which feature a high power input and relative insensitivity to overvoltage should therefore be connected close to the alternator,

whereas voltage-sensitive loads with a low power input should be connected close to the battery.

Power output of the consumers

Consumer classification

The electrical consumers have a variety of switch-on durations. Here the operative distinction is between:

- continuous loads, which are always switched on (e.g. electric fuel pump, engine management),
- long-term loads, which are switched on where necessary and then remain on for an extended time (e.g. low-beam headlights, car radio, electric radiator fan),
- short-term loads, which are only switched on for brief periods (e.g. turn-signal lamps, stop lamps, electrical seat adjustment, power-window units).

Running-time-dependent electrical load requirements

The electrical load requirements encountered during vehicle operation are not constant. The first minutes after startup are generally characterized by high demand (e.g. heated rear window, seat heating, door-mirror heating), followed by a sharp drop in electrical load requirements.

These consumers are switched off after a few minutes. The electrical load requirements are then determined predominantly by the continuous loads and the long-term loads.

No-load-current consumers

Different ECUs and consumers require a power supply even when the vehicle is parked. The no-load current is composed of the sum total of all these switched-on consumers. Most of these consumers switch off shortly after the engine is turned off (e.g. interior lights). Some, however, are always active (e.g. anti-theft alarm system).

An unexpectedly high no-load current can also occur when, for example, shutdown of the ECU interconnection does not work correctly or recurring "Wake-Ups" cause an ECU to frequently reactivate the interconnection when the vehicle is parked. The control unit networking must be configured and validated for this.

The no-load current must be supplied by the battery. The maximum value for the no-load current is defined by the vehicle manufacturers. Battery dimensioning is based among other things on this value. Typical values for the no-load current in a passenger car are approx. 3 to 30 mA.

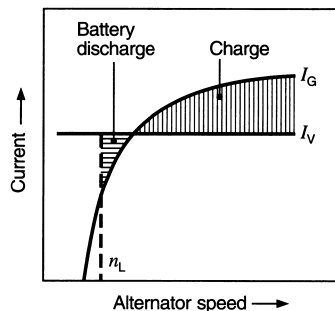
Current output of the alternator

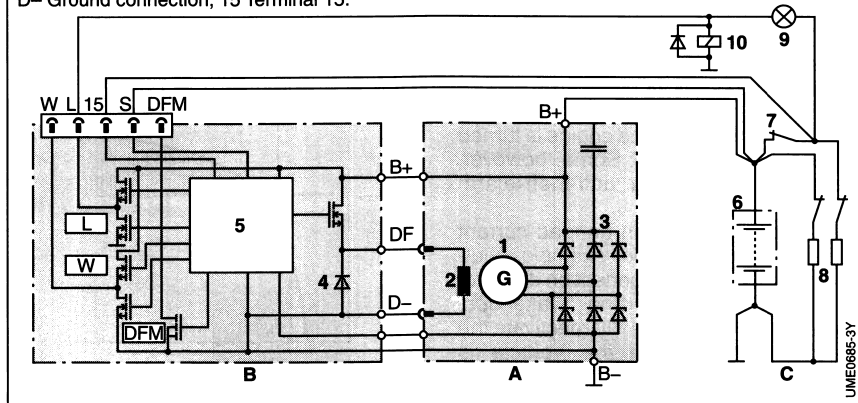
Important component parts of the alternator are the stator (Figure 5) and the rotor, which is driven via the V-belt by the crankshaft. An alternating voltage is induced in the three stator windings (see Three-phase alternator) when a current flows in the rotor coil (excitation current) and a magnetic field is thereby built up. The excitation current is tapped from the generated alternator current (self-excitation). The induced voltage is dependent on the rotor speed and the level of the excitation current. The generated alternating voltage is rectified by diodes.

The voltage induced in the alternator is dependent on the alternator speed and thus on the engine speed. Therefore the voltage is low at low speeds. For an engine idling speed of n_L , the alternator can only supply some of its rated current if it has a conventional turns ratio (crankshaft speed to alternator speed) ranging from 1:2.5 to 1:3 (values for passenger cars;

Figure 4: Alternator current output I_G as a function of alternator speed

I_V Equipment current draw,
 I_G Alternator current,
 n_L Engine idle speed.





B+ corresponds to the specified setpoint value. The frequency of the PWM signal is 40 to 200 Hz; the pulse duty factor is dependent on how much power is demanded by the consumers. In the case of a load variation the vehicle system voltage changes, whereupon the regulator adjusts the excitation field by adapting the PWM signal in such a way that the voltage is compensated.

The connection of the excitation winding is known as DF (dynamo field). The alternator regulator outputs the PWM signal as a DFM (DF monitor) to notify other ECUs of the alternator capacity utilization.

The regulator requires the battery-voltage value in order to regulate. It obtains this value via terminal B+. In the case of a long supply line and high currents on the line between alternator and battery, the voltage drop between the battery and the regulator can be high to the extent that power generation by the alternator is too low and the battery is possibly insufficiently charged. This problem can be remedied by the S-terminal, which supplies the regulator with battery voltage via a cable which is separately connected to the battery positive terminal.

The regulator bus connection (e.g. LIN bus) allows the system to vary the setpoint value to which the voltage is to be regulated. This makes possible functions such as, for example, recuperation. The Load-Response Driving function effects ramp regulation of the alternator voltage back to the setpoint value during vehicle operation after the connection of a high load and the associated sudden drop in the alternator voltage. This function prevents the alternator from abruptly subjecting the engine to load.

Charge indicator lamp

The charge indicator lamp is activated by the alternator regulator. It comes on with "ignition on" and goes out when the alternator is supplying current. The regulator activates the charge indicator lamp as soon as it detects a fault (e.g. alternator failure due to V-belt break, open circuit or short circuit in the excitation circuit, open circuit in the charging cable between the alternator and the battery).

Charging the battery

Due to the chemical processes that take place in the battery, the ideal battery charge voltage has to be higher at low temperatures and lower at high temperatures. The gassing voltage curve shows the maximum permissible voltage at which the battery does not produce gas significantly. The alternator regulator limits the voltage if the alternator current I_G is greater than the sum of the consumer equipment current draw I_V and the temperature-dependent, maximum permissible battery charging current I_B .

Regulators are normally mounted on the alternator. If there are significant deviations between the temperatures of the voltage regulator and the battery electrolyte, it is better to monitor the voltage-regulation temperature directly at the battery. This is possible in vehicles with a battery sensor. The temperature value is conveyed by means of a communication interface (e.g. LIN bus) (see Battery sensor).

The arrangement of the alternator, battery and consumers influences the voltage drop on the charging cable and thus the charge voltage. The total current $I_G = I_B + I_V$ flows through the charging cable if all electrical equipment is connected to the battery. The charging voltage is accordingly less due to the high voltage drop. If all consumers are connected on the alternator side, the voltage drop is lower and the charging voltage is higher. The regulator can take into account the voltage drop by measuring the actual voltage value directly at the battery.

Electrical-system structures

One-battery vehicle electrical system

Figure 1 depicts a one-battery vehicle electrical system, as featured predominantly in passenger-car applications. Working as an energy accumulator is a battery which both supplies the current for the starting sequence and delivers the power supply to the consumers in the event of no alternator output (engine switched off) or insufficient alternator output (idling phases). This is the most widely used concept today in that it is the most cost-effective solution for supplying power in motor vehicles.

In the design of a vehicle battery for the one-battery electrical system which supplies both the starter and the other consumers in the vehicle electrical system, a compromise has to be found between different requirements. During the engine starting sequence, the battery is subjected to high current loads (300 to 500 A). The associated voltage drop has an adverse effect on certain electrical equipment (e.g. undervoltage reset on units with microcontrollers) and should be as low as possible.

By contrast, only comparatively low currents flow during standard vehicle operation. Battery capacity is the salient factor in providing a reliable current supply. Neither properties – output nor capacity – can be optimized simultaneously.

Two-battery vehicle electrical system

In vehicle electrical systems with two batteries – starter battery and general-purpose battery – the “high power for starting” and “general-purpose electrical supply” functions are separated by the vehicle electrical system control unit (Figure 6) to make it possible to avoid the voltage drop during the starting process, while ensuring reliable cold starts, even when the charge level of the general-purpose battery is low.

Starter battery

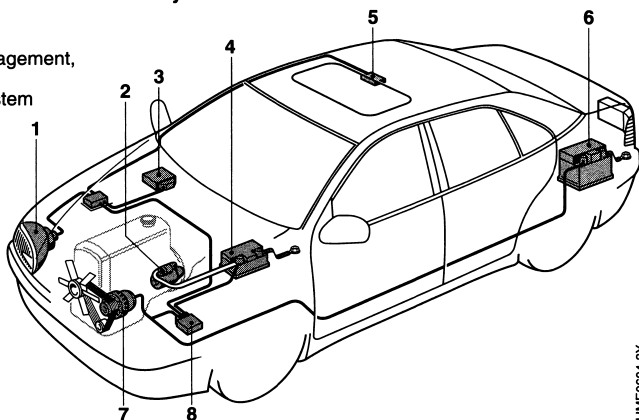
The starter battery must supply a high amount of current for only a limited period of time (during starting). It is therefore designed for a high power density (high power for low weight). Compact dimensions allow installation in the immediate vicinity of the starter motor with short connecting cables (low voltage drop on the line). The capacity is reduced.

General-purpose battery

This battery only supplies the vehicle electrical system (excluding the starter). It supplies currents to the electrical-system consumers (e.g. approx. 20 A for the engine-management system) and must therefore be able to store and provide large amounts of energy. It also has a high cycle stability. This means it can be charged and discharged very often before the performance criteria of the battery are

Figure 6: Two-battery vehicle electrical system

- 1 Lighting system,
- 2 Starter,
- 3 ECU for engine management,
- 4 Starter battery,
- 5 Further electrical-system consumers (e.g. electric sliding-sunroof operation),
- 6 General-purpose battery,
- 7 Alternator,
- 8 Electrical-system ECU.



no longer met. Dimensioning is based essentially on the capacity reserves required for activated consumers, the consumers that operate with the engine switched off (no-load-current consumers, e.g. receiver for central-locking radio remote control, anti-theft alarm system), and the minimum permissible charge level.

Vehicle power supply control unit

The vehicle power supply control unit in a two-battery vehicle electrical system separates the starter battery and the starter from the rest of the vehicle electrical system provided this can be supplied with sufficient power by the general-purpose battery. It therefore prevents the voltage drop that occurs during starting, affecting the performance of the vehicle electrical system. When the vehicle is parked, this prevents the starter battery from becoming discharged by electrical equipment that draws current when switched on and by no-load-current consumers.

The 12 V battery can be charged at higher voltage than the usual alternator voltage in the vehicle. The voltage level is limited by consumers, e.g. the bulbs, whose service life severely deteriorates with the voltage. By separation of the starter battery from the remainder of the vehicle electrical system, there are theoretically no limits for the charge voltage level within the starter battery. It can therefore be raised to the "ideal" value by means of a DC/DC converter (e.g. 15 V). This is dependent on the temperature and on the state of charge. Charging duration is minimized with the increased charge voltage.

If there is no charge in the general-purpose battery, the control unit is capable of provisionally connecting both vehicle electrical systems. This means that the vehicle electrical system can be sustained using the fully-charged starter battery. In another possible configuration, the control unit for the starting operation would connect only the start-related consumers to whichever battery was fully charged.

Electrical-system parameters

State of charge

The state of charge (SOC) of the battery is one of the most important parameters in the vehicle electrical system. It can be defined as the ratio of the amount of charge still stored in the battery (actual state of charge) to the maximum amount of charge which the fully charged battery when new can store:

$$\text{SOC} = \frac{Q_{\text{act}}}{Q_{\text{max}}}$$

The value Q_{max} is obtained when a fully charged battery is discharged at discharge current I_{20} – corresponding to a twentieth of the nominal capacity in amperes (5 A for a 100 Ah battery) – until the cutoff voltage of 10.5 V is reached. The amount of charge which was drawn during this discharge process corresponds to Q_{max} .

Since in this way Q_{max} is only accessible by means of one measurement (integral of the current over the time, i.e. current and time measurement), the definition can also frequently be provided by the nominal capacity of the battery, which can be found on the label, where: $Q_{\text{max}} = K_{20}$ (nominal).

The currently stored amount of charge Q_{act} is obtained from the difference between Q_{max} and the amount of charge drawn during the discharge of the fully charged battery.

The state of charge of the battery correlates directly with the electrolyte density, where furthermore the steady-state voltage of the battery is proportional to the electrolyte density. The voltage value which is obtained when a stable voltage final value is assumed after the battery charging or discharging process is referred to as steady-state voltage. This can, owing to the slow diffusion and polarization processes in the battery, take several days, especially after long charging phases. The steady-state voltage is measured at the terminals.

The state of charge is defined as follows:

$$\text{SOC} = \frac{(U_{\text{current}} - U_{\text{min}})}{(U_{\text{max}} - U_{\text{min}})}$$

where
 U_{current} : Current steady-state voltage.
 U_{max} : Steady-state voltage of the fully charged battery (SOC = 100 %).
 U_{min} : Steady-state voltage of the battery at SOC = 0 %. Because the dependence of the steady-state voltage on the state of charge is nonlinear for low states of charge (approx. less than 20 %), the value linearly extrapolated to SOC = 0 % must be used here.

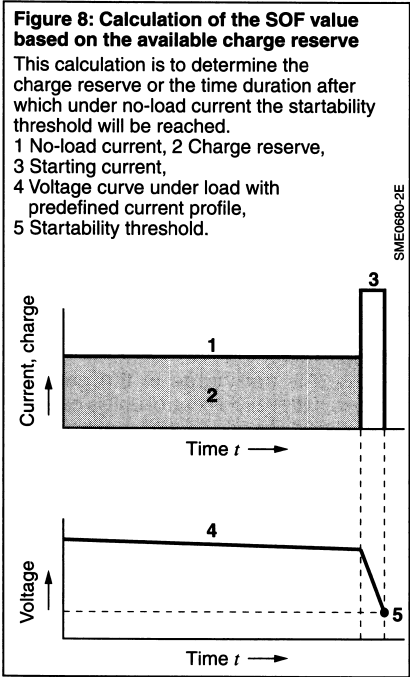
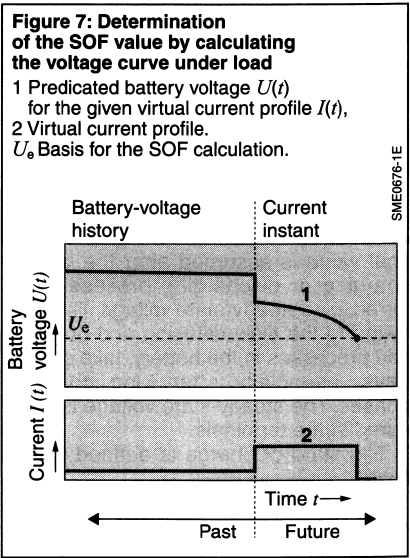
In this way, it is possible to infer the state of charge from the measured steady-state voltage.

Functional and performance capability

The capability of the battery to meet a specified functional or performance requirement in its current state – e.g. providing the starting power for the internal-combustion engine – is called the SOF (State of function). The SOF is application-specific and can therefore not be defined generally. For example, the SOF can be used not only as a measure of startability, but also for evaluating the current performance capability of the battery to supply other electrical heavy current consumers, e.g. electrical power steering.

The current performance capability of the battery is evaluated using the SOF by pre-calculating the voltage drop at battery load with a predefined current profile. If the precalculated battery voltage U_e drops below a specified threshold, this means that the battery is no longer delivering the required performance (e.g. for an engine start) (Figure 7).

Moreover, it is also possible to query the current remaining charge or the discharge duration which states how long the battery can continue to deliver the required performance. An application example of this is how long a vehicle can be parked at a known no-load current consumption without losing startability. In this case, the SOF does not provide the voltage drop at high-current load, rather the remaining charge reserve or the discharge duration until the startability threshold is no longer reached (Figure 8).



As already mentioned, the SOF is determined on the basis of the current battery state, i.e. it depends on the current state of charge, the temperature and the state of health of the battery. These variables have to be determined by the battery-status recognition (see Battery sensor) for SOF calculation.

State of health

Depending on the respective operating and ambient conditions, different aging processes take place in a lead storage battery, which can, for example, lead to an increase in internal resistance (caused by corrosion) or to capacity losses (caused by active mass loss or sulfating) and therefore deteriorate the general performance and storage capability of the battery, i.e. its state of health (SOH) over the service life.

The state of health of the battery with regard to its storage capability can, for example, be expressed by the ratio of current capacity K_{20} to nominal capacity of the battery when new $K_{20\text{new}}$:

$$\text{SOH} = K_{20} / K_{20\text{new}} \cdot 100 \, \%.$$

Further (application-dependent) SOH quantities can be derived from the corresponding SOF variables by calculating them not for the current battery state, rather with defined values for state of charge (e.g. SOC = 100 %) and battery temperature (e.g. 25 °C) to achieve the desired aim of only factoring the dependence on the state of health into the SOH quantity.

Whereas the SOF states how well a performance requirement can be met in the current state of the battery, the corresponding SOH variable states how well the battery will meet this performance requirement generally in the current state of health. For example, in this way an SOH variable which calculates the battery's remaining minimum performance capability for the start-stop function can be used to permanently deactivate this function when the battery is severely aged, in order to prevent the risk of breakdowns.

Alternator capacity utilization

The current flowing in the alternator excitation winding determines the voltage induced in the stator windings. The alternator regulator regulates the required excitation current by means of a pulse duty factor (PWM signal). DF (dynamo field) is the terminal through which the excitation current is supplied. The pulse duty factor of the PWM signal indicates the alternator capacity utilization, i.e. whether the alternator still has reserves and can supply even more current for additionally connected loads.

The alternator regulator additionally outputs this signal as a DFM signal (DF monitor). Regulators with a bus interface apply this pulse duty factor to the bus. The excitation current is also output in amperes. Different ECUs evaluate the DFM signal in order, for example, to switch off the seat heating or the windshield heater when the alternator is subject to high capacity utilization.

Electrical energy management

Motivation

Reduced fuel consumption

One of the primary goals of motor-vehicle manufacturers is to reduce fuel consumption and greenhouse gases, in particular CO₂. This is achieved by optimizing the energy flows in motor vehicles. Measures to achieve this goal include:

- Avoiding idling losses by using the start-stop function (automatic engine switch-off and restarting for example when waiting at traffic signals on red).
- Increasing the efficiency of electrical power generation by optimizing the alternator and applying intelligent alternator activation (recuperation).
- Electrically driven accessories to facilitate activation to suit demand by means of isolation from the internal-combustion engine.

Electrical power demand

Additional comfort and convenience functions and electrified accessories give rise to increasing electrical power requirements and at the same time to a reduced range of speed for electrical power generation (e.g. due to start-stop operation). New comfort, convenience and safety

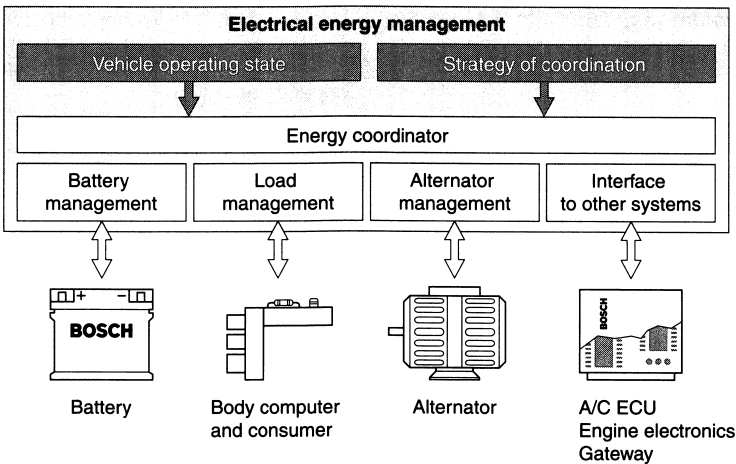
functions (e.g. electrical power steering, electric water pump, PTC auxiliary heater, electric climate control in vehicles with start-stop function) require additional electrical power, so much so that it is useful to integrate an electrical energy management system (EEM).

Purpose of electrical energy management

Electrical energy management controls the energy flows and at the same time safeguards the electrical power supply in order to maintain vehicle startability and to reduce breakdowns caused by flat (discharged) batteries. Electrical energy management also stabilizes the battery voltage and optimizes the availability of comfort and convenience systems – even when the engine is stopped. This can be achieved by safeguarding a positive or at least equalized charge balance during vehicle operation and by monitoring the power demand when the engine is stopped. Furthermore, peak loads can be reduced by the coordinated switching of electrical consumers. This is coordinated in the electrical energy management system (Figure 9).

The effects of the measures taken sometimes conflict with one another. For example, switching off comfort and convenience

Figure 9: Electrical energy management (EEM)



nience consumers results in loss of comfort and convenience, while disabling the start-stop function results in increased fuel consumption. Different vehicle manufacturers prefer different measures, and the possible measures for safeguarding the charge balance are prioritized accordingly.

Functions of electrical energy management

Load management in no-load mode (no-load-current management)

The no-load-current management implemented in the battery sensor by means of software regularly monitors the battery status and thus startability when the engine is stopped. With the aid of precise battery-status recognition it is possible to optimize the availability of consumers by means of no-load-current management, i.e. the operating time of the comfort and convenience consumers can be maximized. In the event of an imminent loss of startability, electrical energy management can, for example, send a message to the display module in order to notify the user. In addition, when the startability limit is approached, load management will reduce the power consumption (e.g. by reducing the power consumption of the A/C fan) right down to shutting down individual consumers in order to maintain startability for as long as possible. Examples of such comfort and convenience consumers are the auxiliary heater, infotainment, navigation system, radio, and telephone.

Load management during vehicle operation

The function of electrical energy management with the alternator active is, in addition to load management, principally alternator management including a recuperation function and the energy-management interface to other systems such as, for example, engine management.

Switching of consumers

Load management coordinates the activation and deactivation of consumers in order to reduce power peaks. Load management is also involved in controlling the high-performance heating systems (windshield heater and PTC auxiliary heater).

In vehicle operation, too, safeguarding restartability is the primary function of electrical energy management. In critical battery states, load management reduces the electrical power demand in order to recharge battery as quickly as possible. Reservoir-type comfort and convenience consumers (heating systems) are switched back by preference, because intelligent activation can be used to delay for as long as possible perceptible deviations from the nominal performance.

There are limits to deactivating comfort and convenience functions in that this will only be accepted by the user in rare exceptional circumstances. The vehicle electrical system must therefore be configured in such a way that these situations only occur rarely. Noticeable effects must be indicated to the user in order to explain the performance that is deviating from normal operation.

Increasing the alternator output

As an alternative or complement to reducing the electrical power demand, it is possible by increasing the engine speed to increase the electrical power generation by the alternator (e.g. idle-speed increase or disabling of engine stop during start-stop operation). For example, to increase the idle speed, electrical energy management issues a request via the data bus to the engine management. These measures have a direct influence on fuel consumption and noise generation, and must therefore be optimally matched to the individual vehicle.

During a recuperation the vehicle's kinetic energy is converted at least partially into electrical energy and delivered to the battery for storage. This function requires an alternator that can be controlled via an interface to input the desired operating voltage and a battery sensor for recognizing the battery status. The function itself can be partitioned in the engine electronics, a gateway or a body computer.

During overrun fuel cutoff an increased desired voltage is input for the alternator in order to charge the battery intensively. Electrical power is generated at this operating point without fuel consumption. In driving states with poor efficiency in terms of electrical power generation the alternator voltage is decreased and the battery slowly discharged again in order to minimize the fuel demand for electrical power generation.

A fully charged battery cannot absorb charge. For this reason, recuperation is only possible with a partially charged battery (partial state of charge, PSOC). This is a departure from the conventional charging strategy, the objective of which is

to achieve as fully charged a battery as possible. A minimum battery status required for startability must not under any circumstances be undershot, i.e. the current battery status must be known to electrical energy management.

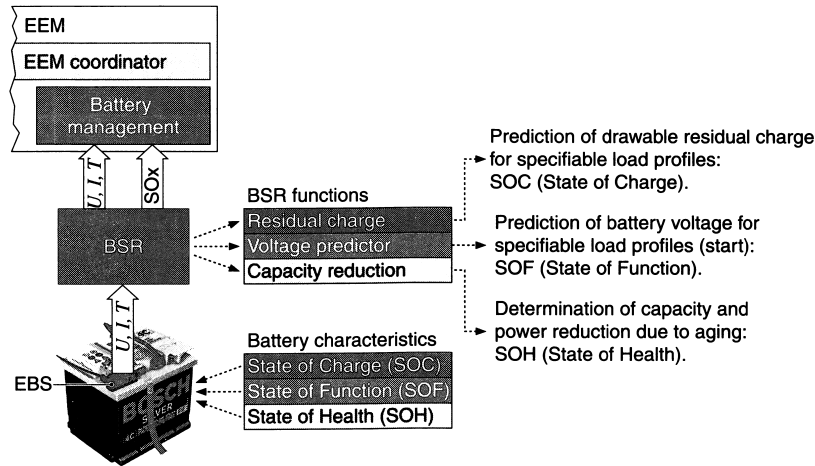
The recuperation function results in an increased cyclical variation of the battery, the influence of which on battery aging must be tested on an application-specific basis. The use of AGM batteries (absorbent glass mat) to increase the possible energy throughput (throughput in Ah over the service life, the throughput critical to service life increases by a factor of 3) is therefore recommended.

The recuperation algorithm must take into account the influence of voltage changes on the consumers, since these can be observable (e.g. change in the speed of the A/F fan or light flickers).

Recuperation provides for fuel savings in the range of 1 to 4 %, depending on the cycle and configuration of the function.

Figure 10: Interaction of battery sensor, battery-status recognition and electrical energy management

EEM Electrical energy management, BSR Battery-status recognition, EBS Electronic battery sensor
SOC State of charge, SOH State of health, SOF State of function, U Battery voltage, I Battery current, T Battery temperature.



Battery-status recognition and battery management

Function

A crucial element to sound electrical energy management is a battery-status recognition facility (BSR) which reliably calculates the capability of the battery. Algorithms for battery-status recognition normally use as input variables the measured variables of battery current, voltage and temperature. On the basis of these variables the state of charge (SOC), the state of function (SOF) and the state of health (SOH) of the battery are determined and made available to electrical energy management as input variables (Figure 10).

A battery sensor which measures the battery current and voltage directly is used to measure the battery variables. The battery temperature is determined by way of a temperature measurement in the vicinity of the battery, since direct measurement of the battery electrolyte temperature in the vehicle would require an intervention in the battery, which is currently not possible.

Example

An example of a battery-status-recognition function is determining startability on the basis of the SOF. With the SOF the future behavior of the battery when subjected to starting current is predicted. In other words, battery-status recognition determines the battery-voltage dip for a given starting-current profile (Figure 7). Because the minimum voltage level for a successful start is known, the predicted voltage dip provides a measure of current startability. Depending on the interval between the predicted voltage dip and the startability limit, electrical energy management defines measures for maintaining or improving startability.

Battery sensor

The battery measured variables of current, voltage and temperature must be sensed very precisely, dynamically and synchronously. Particularly the measurement of currents in the range of a few mA through to starting currents of more than 1,000 A makes great demands on the sensor system. An electronic battery sensor (EBS) is mounted directly on and combined with the battery terminal. Because the terminal compartment is standardized in accordance with DIN 50342-2 [2], application on different batteries is not necessary.

Current is measured using a special manganin shunt. The core of the battery sensor's electrical wiring is an ASIC which contains among others a powerful microprocessor for recording and processing measured values. The battery-status-recognition algorithms are also processed on this microprocessor. Communication with higher-level ECUs is via the LIN bus.

As well as calculating the battery status for electrical energy management, the battery sensor can also be used for other functions. For example, precise sensing of current and voltage can also be used for prompted troubleshooting in production and workshops (e.g. searching for faulty no-load-current consumers).

References

- [1] K. Reif (Editor): Bosch Autoelektrik und Autoelektronik, 6th Edition, Vieweg+Teubner, 2011.
- [2] DIN EN 50342-2 (2008): Dimensions of batteries and marking of terminals.

Vehicle electrical systems for hybrid and electric vehicles

The electrical system of a vehicle with start/stop system is very similar to a conventional vehicle electrical system (see Conventional vehicle electrical systems). In contrast, vehicle electrical systems for mild, full and plug-in hybrid vehicles and those for electric vehicles usually have a high voltage level and thus differ significantly from the electrical system of a conventional vehicle.

The electrical system of a hybrid or electric vehicle has the following chief functions:

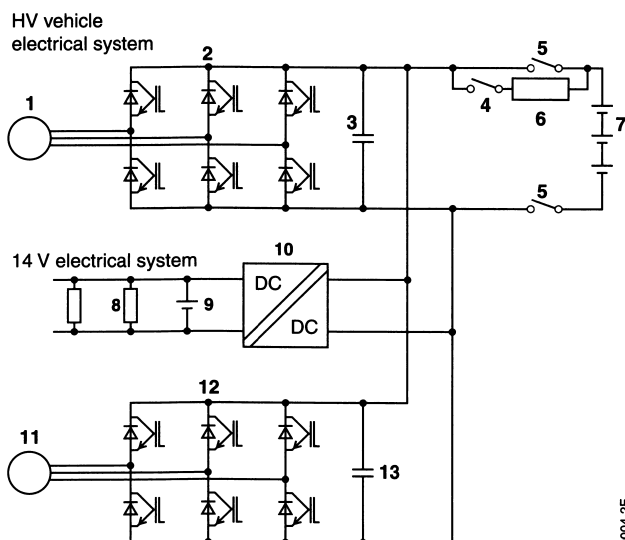
- storing excess electric energy from the powertrain,
- outputting electric energy to the powertrain,
- reliable supply of the electrical consumers,
- for plug-in hybrid and electric vehicles, storing energy from the public power supply and supplying the vehicle with it during operation.

Vehicle electrical systems for mild and full hybrid vehicles

The function of a mild or full hybrid vehicle (see Hybrid drives) requires a large amount of electric power, 8 to 60 kW. This cannot be provided on the 14 V voltage level in a sensible way. Therefore an HV vehicle electrical system (HV stands for High Voltage) with a voltage in the range of 42 to 750 V is additionally required. However, the 14 V standard electrical system is still required to supply the 14 V consumers in the vehicle. The individual consumers are supplied from the corresponding vehicle electrical system according to their power requirements (Figure 1). Generally, for cost reasons, automakers attempt to make do with standard 14 V components, as these are available cheaply and in large quantities.

Figure 1: Electrical system of a vehicle with parallel hybrid drive

- 1 Electrical machine,
- 2 PWM inverter,
- 3 DC link capacitor,
- 4 Pre-charging contactor,
- 5 Main contactor,
- 6 Pre-charging resistor,
- 7 HV battery,
- 8 14 V consumer,
- 9 12 V battery,
- 10 Electrically isolated DC/DC converter,
- 11 Air-conditioning compressor,
- 12 PWM inverter,
- 13 DC link capacitor.



HV vehicle electrical system*Layout*

The HV vehicle electrical system consists of an HV battery, at least one PWM inverter to power the electric motor (electric machine, e-motor), other high-output or HV consumers (e.g., electric air-conditioning compressor) and an electrically isolated DC/DC converter to supply the 14 V vehicle electrical system (Figure 1).

Operating principle

The battery cells are energized via the contactors integrated into the HV battery. They provide buffer storage during operation. When the vehicle is switched off or if there is an accident, the HV vehicle electrical system is de-energized via the contactors, limiting the hazardous high voltage to the battery block.

The PWM inverter in the power class from 10 to 200 kVA generates a three-phase system from the high direct voltage with a variable current intensity and rotating field frequency for the electric machine.

Power is supplied to the HV vehicle electrical system when the electric machine is in generator mode.

The electrically isolated DC/DC converter transmits electrical energy from the HV vehicle electrical system to the 14 V vehicle electrical system. Power is thus supplied to this low-voltage vehicle electrical system from the HV vehicle electrical system.

An example of an additional component of the HV vehicle electrical system can be an electric air-conditioning compressor, which requires a maximum electric power of 3 to 6 kW depending on the vehicle.

HV electrical system for parallel or quasi-parallel hybrid drives

The topologies of the vehicle electrical systems for mild and full hybrids with only one electric motor each are very similar. The vehicle electrical system of a mild hybrid (compared to the full hybrid) makes do with a lower energy accumulation and lower output capacity, as the vehicle can "crawl" electrically for a very short time at most.

The primary flow of energy of a vehicle with parallel hybrid drive is from the electric machine to the HV battery and vice

versa. There is also a small flow of energy via the DC/DC converter to the 14 V vehicle electrical system or to other HV consumers. The structure in Figure 1 is useful for implementing this in the most efficient and cost-effective manner possible, i.e. with few converters.

HV electrical system for power-split or semi-serial hybrid drives

Vehicles with two electrical machines that are run mostly serially (e.g. power-split hybrids) require a different electrical system topology.

In power-split hybrid vehicles or serial or parallel-serial hybrid vehicles, for the majority of the operating time, the electrical machines run in serial or partially serial operation. This means that one of the electric motors runs primarily in generative mode and the other in motor mode. Due to the large amounts of energy that are transmitted via the two electrical machines and the PWM inverters, these components should be operated in their optimal working range.

The battery voltage is set at the defined output of the battery. The intermediate circuit – consisting of the DC capacitor (DC link capacitor) and the associated conductors and, optionally, an electrically conductive DC/DC converter (high-output DC/DC converter) – distributes the energy on the high direct-voltage level in the vehicle. It uses DC link capacitors to stabilize the direct voltage for sudden load variations (e.g. at the PWM inverter). For this concept, however, there are two principal DC links that are separated by the high-output DC/DC converter (Figure 2). A high-output DC/DC converter between the battery and DC link is useful for decoupling the DC link voltage for the electric motor from the battery voltage and enabling higher machine speed at a given battery voltage (Figure 2). Thus the DC link voltage can be adjusted as necessary between the level of the battery voltage and a significantly higher voltage value (2 to 2.5 times the battery voltage) [1]. The maximum voltage is determined via the required maximum output and the design of the electrical machines. The currently configured DC link voltage can be selected such that it is just above the

maximum value of the rectified induced voltages of the electrical machines. This makes it possible to minimize the switching frequency of the inverter switches and thus the electrical inverter losses.

14 V electrical system

The 14 V vehicle electrical system has a similar design for all hybrid vehicles that have both an HV and a 14 V vehicle electrical systems. It is very similar to the 14 V electrical system of a conventionally powered vehicle except for the fact that it usually does not have a starter and the power

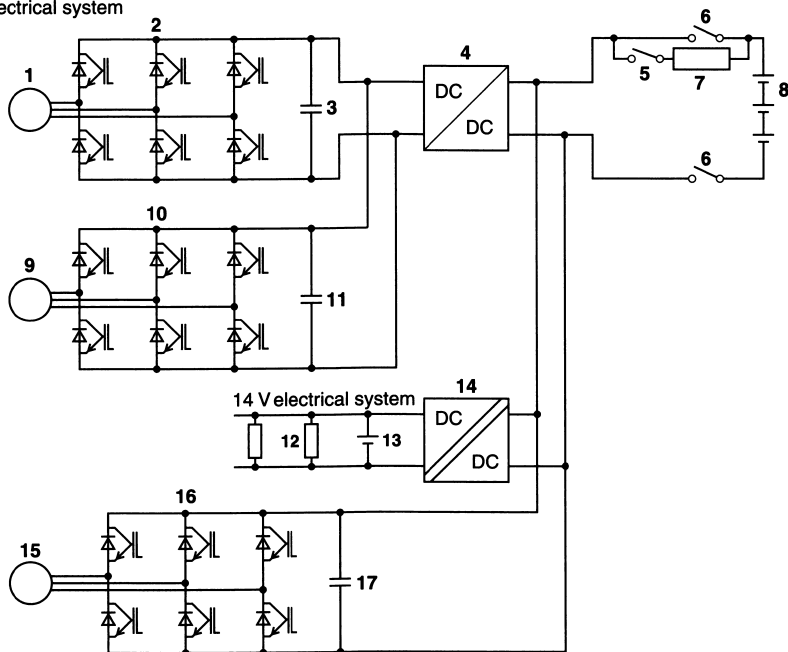
is supplied not by an alternator, but by an electrically isolated DC/DC converter from the HV vehicle electrical system.

If the vehicle can drive or crawl electrically, all assisting functions – such as power steering, cooler pumps or braking system – must be operated electrically so that they are also available when the internal-combustion engine is stopped.

Figure 2: Electrical system of a power-split or serial vehicle

- 1 Electrical machine, 2 PWM inverter, 3 DC link capacitor,
- 4 High-output DC/DC converter, 5 Pre-charging contactor,
- 6 Main contactor, 7 Pre-charging resistor, 8 HV battery,
- 9 Electrical machine, 10 PWM inverter,
- 11 DC link capacitor, 12 14 V consumer, 13 Battery (12 V),
- 14 Electrically isolated DC/DC converter,
- 15 Air-conditioning compressor, 16 PWM inverter,
- 17 DC link capacitor.

HV vehicle
electrical system



Vehicle electrical systems for plug-in hybrid and electric vehicles

Topology

The vehicle electrical system of a plug-in hybrid vehicle (see Plug-in hybrid) mostly corresponds to that of the comparable hybrid vehicle without external charging capability, other than having a larger battery with a greater energy storage capacity and a charging device.

For a purely electric vehicle, the topology of the parallel hybrid vehicle with a larger battery and a charging device is usually used (Figure 3). A charging device can be used that draws electrical energy from a public three-phase or alternating current power supply and uses it to charge the battery in a controlled manner. The battery management system tells the charging device the charging output it needs. For safety and to protect against overvoltage, this charging device usually has an electrically isolated design.

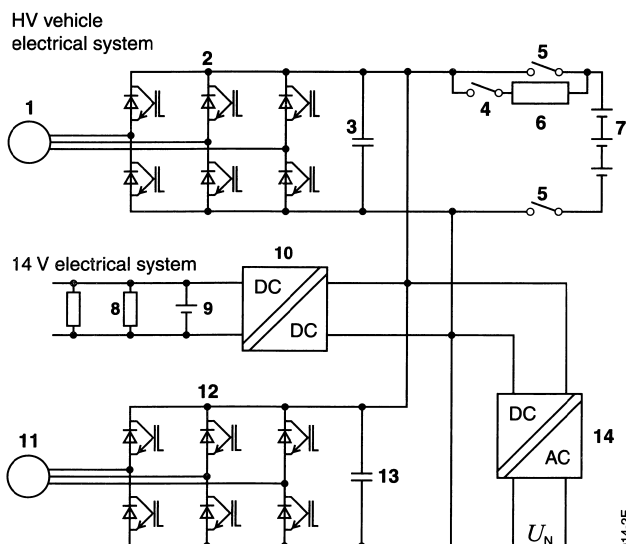
Alternatively, the battery of an electric vehicle can also be charged with direct current from an externally controlled charging station. In this case, all that is required is a plug-in connection to the HV battery and a communication interface between the battery management and charging station to specify the charging output.

Efficiency

For electric vehicles, the efficiency of the vehicle electrical system is critical, as it has a direct effect not only on consumption, but also the range and thus the battery size needed. As a result, more expensive and more efficient components can reduce the total costs of the vehicle, as they make the same range possible with a smaller battery. Therefore, for many components of the vehicle electrical system, a review should be carried out to determine whether a less-expensive standard component can be used or it is worthwhile to develop a new, more efficient component.

Figure 3: Electrical system of an electric vehicle

- 1 Electric drive,
- 2 PWM inverter,
- 3 DC link capacitor,
- 4 Pre-charging contactor,
- 5 Main contactor,
- 6 Pre-charging resistor,
- 7 HV battery,
- 8 14 V consumer,
- 9 Battery (12 V),
- 10 Electrically isolated DC/DC converter,
- 11 Air-conditioning compressor,
- 12 PWM inverter,
- 13 DC link capacitor,
- 14 AC/DC converter (charging device).



Charging strategy

Cyclical variation

Generally, cyclical variation (cyclical charging and discharging) damages the battery. The higher the cycle strokes, the greater the damage will be. However, cyclical variation is required to increase the efficiency of the powertrain, for example with electric driving followed by recuperation. Thus the charging strategy and the selected size of the battery are a compromise between battery life, battery costs and weight on the one hand and good efficiency of the hybrid powertrain or longer range for electric vehicles on the other.

Usually, the thermal aging processes of the battery cells are accelerated significantly at a high state of charge (SOC). Therefore, the charging strategy should avoid combining a high state of charge and high temperature of the cells.

Operating strategy for hybrid vehicles

Normally, the system attempts to keep the battery of a hybrid vehicle in an SOC window of approx. 50 to 70 %. If the SOC exceeds this window, there is no operating point shift of the internal-combustion engine and no more recuperation.

When the lower SOC limit ($SOC_{\min \text{ charge}}$) of approx. 50 % is reached, it is necessary to ensure that an adequate battery discharge power is still possible. Therefore, when the lower SOC limit is reached, battery recharging increases if no boost energy is required at the moment. Only when a much lower SOC limit is reached is the discharge output slowly reduced to zero. In normal vehicle operation, the vehicle almost never reaches this lower discharge limit, and the driver always experiences nearly identical acceleration behavior.

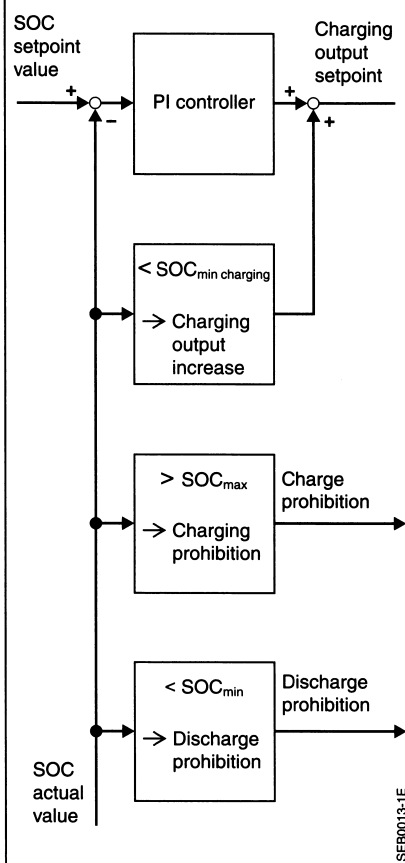
The lower SOC limit also plays an important role for reliably maintaining startability and preventing deep discharge, which is detrimental to service life.

The charging strategy (Figure 4) is usually implemented in the engine control unit or in a special hybrid control unit.

Operating strategy for electric vehicles

In a pure electric vehicle, there is only one source of energy – the battery. Therefore, the operating strategy must fulfill the driver's command from this source, regardless of the state of charge. Therefore, strong cyclical variation is inevitable to attain the necessary range of the vehicle at a reasonable battery size. Here, the SOC limits are placed such that there are no effects that are very detrimental to service life, such as those due to electrolyte decomposition in case of overcharge.

Figure 4: Charging strategy of a hybrid vehicle in driving mode
SOC (State of Charge).



Depending on the battery system, the usable SOC range is between approx. 10% and 90%.

Operating strategy for electric vehicles with range extender

For an electric vehicle with range extender – a small internal-combustion engine with an alternator that supplies electrical energy to the HV vehicle electrical system – the range extender is activated during a longer journey or if a lower SOC limit value is reached. As the output of the range extender is usually low, it is operated constantly at full load and recharges the battery where applicable.

Operating strategy for plug-in hybrid

A plug-in hybrid can still drive with the combustion engine. Therefore, its charging strategy is a mix of that of an electric vehicle and that of a hybrid vehicle. To optimize fuel consumption, the strategy attempts to maximize the amount of

electric driving. Only if this is not possible, such as during a long journey, does the system switch to hybrid operation with a charging strategy that is similar to that of a hybrid vehicle, usually with lower SOC limits.

When charging the battery from the power grid, the battery charger or the public power grid is usually the limiting element. Therefore, in many cases, the battery is charged using the currently available charging power or charging current until a voltage limit is reached; then, the charging power is then successively withdrawn until the end-of-charge voltage is reached.

References

[1] S. Sasaki, E. Sato, M. Okamura: The Motor Control Technologies for the Hybrid Electric Vehicle; Toyota Motor Corporation.

Starter batteries

Requirements

The starter battery is used to start the internal-combustion engine and to provide electrical energy for lighting and other components (SLI, Starting, Lighting, Ignition) if the generator does not provide any energy or enough energy.

The battery in the vehicle electrical system

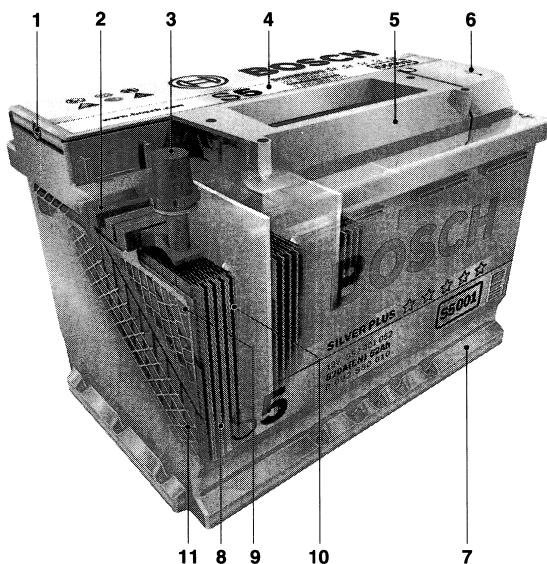
The performance requirements for starter batteries in modern motor vehicles are very high. Diesel engines and large-volume gasoline engines have high cold-cranking power requirements with high starting currents, particularly at low temperatures. When the engine is running, the electric components are usually supplied directly from the generator. When the engine speed is low or at a standstill, on the other hand, it is supplied partially or completely from the battery. If a vehicle is parked for days or weeks, a peak coil

current of typically 3 to 30 milliamperes must be supplied. This also includes the much higher temporary flow current consumption for ventilators, pumps and electronic components immediately after switching off the internal-combustion engine, as well as for comfort and convenience consumers operated while the vehicle is parked, such as entertainment and communication electronics and for the auxiliary heater, if present. The battery must also be able to start the vehicle, even after it has been parked for extended periods.

In addition to the uniform energy supply, the battery in the vehicle electrical system covers high dynamic current pulses which cannot be delivered by the alternator as quickly (for transient processes, such as switch-on processes in the electrical power steering). Furthermore, due to the very high inherent natural capacitance of the double-layer capacitor of a few farad, the battery smooths ripples in the auto-

Figure 1: Structure of a starter battery

- 1 Gas outlet opening,
- 2 Electrode connector,
- 3 Battery terminal,
- 4 Double cover with labyrinth structure,
- 5 Carrying handle,
- 6 Terminal-post cover,
- 7 Bottom rail,
- 8 Electrode block (consisting of a set with positive electrodes and a set with negative electrodes),
- 9 Positive electrode, with stamped grid and positive active materials,
- 10 Envelope separator,
- 11 Negative electrode, with expanded grid and negative active materials.



motive electrical system current, which helps minimize EMC problems (electromagnetic compatibility).

The rated voltage of the vehicle electrical system is 14 V for passenger cars and 28 V for commercial vehicles; two identically sized 12 V batteries are connected in series for this.

The battery in innovative vehicle electrical systems

Operating strategies of new vehicles use the battery in an increasingly active manner for reducing fuel consumption and emissions (also see conventional vehicle electrical system). In vehicles with active alternator control, the battery is operated in a partially charged state. The alternator output power is reduced in a targeted manner in operating phases (if necessary, all the load is taken off the alternator is completely discharged), in which the engine is working at poor efficiency or engine output is particularly necessary (e.g. during vehicle acceleration, "Passive Boost"). During these phases, the battery supplies the vehicle with electricity. In phases where the motor is highly efficient and when braking, the battery is then recharged in a targeted manner by raising the charge voltage (see Recuperation).

A start/stop system is used to switch off the engine if the vehicle is not moving (e.g. at a red light). The starter battery then covers the vehicle's entire power consumption of approximately 25 to 70 A. The engine is restarted automatically when the driver wants to pull away.

Depending on the operating conditions, using the battery's storage capacity in this way significantly reduces fuel consumption. The increased charging capacity represents an additional load on the battery, which is accommodated by special designs such as AGM and EFB (see Battery designs). Here, charging the battery well and sufficiently is always a requirement for a level charge balance in order to fulfill these tasks in the long term. A battery status detector is used to monitor the battery status. It generally consists of a sensor attached to the negative battery terminal (EBS, electronic battery sensor for measuring current, voltage and temperature) and software that uses the determined

measurements to identify the status and capacity of the starter battery. Based on these results, the system can make the necessary intervention into the engine management system based on an operating strategy and, for example, decide whether the engine is to be shut off when the vehicle is stationary, whether it is to be restarted automatically when the vehicle is parked for long periods, or how the alternator voltage must be controlled (see conventional vehicle electrical systems).

Numerous vehicles are also equipped with two batteries, for example, to guarantee startability even at a high standby current consumption or to prevent inconveniences (e.g. resetting the infotainment systems) due to the short-term voltage drop in vehicles with start-stop function when restarting automatically (see Two-battery vehicle electrical system).

Hybrid and electric vehicles also have a low-voltage vehicle electrical system of 14 V, on which the majority of the electric components work. This is supported by a 12 V battery, in many cases a high-performance starter battery. In some hybrid vehicles, cold cranking is carried out by a starter motor supplied from this battery (see Vehicle electrical systems for hybrid and electric vehicles).

The battery as component

The requirements mentioned define the electrical properties of the accumulator such as starting power, capacities and charge current absorption. Furthermore, depending on operating conditions, thermal requirements (e.g. due to the installation point in the vehicle and the climate zone) and mechanical requirements (e.g. regarding attachments and vibration resistance) must be observed. The battery should also be maintenance-free, safe in use and environmentally friendly in production. The lead battery features excellent recyclability and achieves the highest recycling rates of all consumer durables at well over 95%, where lead and plastic from old batteries are re-used for battery manufacturing.

The battery in operation

The design of the vehicle's components and the electrical operating concept, as well as the usage profile and driver affect the proper function of the battery and, therefore, the vehicle electrical system. Despite the excellent charge acceptance properties of modern starter batteries, a positive battery charge balance sometimes cannot be achieved during regular, short trips through the city in winter (involving high power consumption and low engine speed) and the state of charge decreases. At low states of charge, not only does the amount of energy still available decrease, but the capability of producing currents sufficient to start the engine decreases as well. Low battery charge levels over longer time periods worsen the cold-cranking characteristics and shorten the service life of the battery.

Battery design

Components

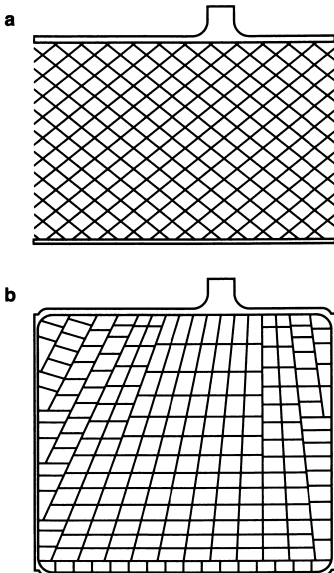
A 12 V starter battery contains six series-connected individually partitioned cells in a polypropylene case (Figure 1). A cell consists of a stack of positive and negative electrodes arranged in alternation, each designed from a lead grid as a carrier and electrical arrestor, filled with porous active materials. Microporous separators isolate the electrodes from each other, where they usually enclose the electrodes of one polarity in a pocket-size format. The separators are made from porous polyethylene filled with silica or from a glass-fiber fleece (AGM, Absorbent Glass Mat).

The electrolyte is in the form of diluted sulfuric acid which fills the pores in the electrodes and separators, and the voids in the cells. The electrodes of one polarity are connected in parallel by plate straps and, using cell connectors, are connected and sealed from openings in the partitions to the neighboring cells or the battery terminals. Battery terminals, cell and plate straps are made of lead alloys.

A lead battery develops an ever-increasing amount of oxygen at the positive electrode and hydrogen at the negative electrode, and this is increased when charging. During this electrolysis process, water is consumed from the electrolytes. The charging gases must be released. The one-piece cover welded to the battery case provides the battery's upper seal and contains various ventilation openings depending on design. On conventional batteries, each cell has a plug, which is used for initially filling the battery with electrolyte, maintenance and the release of charging gases. Maintenance-free batteries usually no longer have a plug. Degassing occurs via an advanced labyrinth system, which prevents liquid from escaping, even if the battery is tilted. However, the ventilation openings, often arranged on the side of the cover, must not be sealed on both sides. Porous sintered bodies permeable to gas (called frits) are installed in front of the ventilation opening inside the cover. These sintered bodies prevent potential flames or sparks outside from backfiring into the inside of the battery.

Figure 2: Conductive grid

- a) Expanded metal grid
- b) Stamped grid



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Conductive grid*Active materials*

In the manufacturing process, the active materials are coated (pasted) into the conducted grid. The positive active materials contain porous lead dioxide (PbO_2 , dark brown). The negative active materials contain porous metallic lead sponge (Pb, metallic gray-green).

Manufacturing and geometry

The lead grid is used for the mechanical mount and electric contact of the active materials. Optimizing the grid structure in terms of electrical conductivity improves the utilization of the active materials. The standard grid manufacturing methods include casting liquid lead into a mold or continuous processes like drawing out and punching from a strip (Figure 2).

Alloy materials

Alloying elements are added to the lead used for the grid to optimize the production process and increase the mechanical strength and corrosion resistance. The strong oxidizing electrochemical potential exposes the positive grid to a continuous corrosion attack. As a result, the cross-sectional area of the webs detaches throughout the duration of use, the electrical resistance is increased and alloying elements are released into the electrolytes. Negative grids, on the other hand, do not have corrosive potential and, therefore, are not affected by corrosion (see Corrosion).

Antimony

If, for example, antimony assumes the function of the hardener for the positive grid, it is gradually released by corrosion and travels diagonally through the electrolyte and the separator to the negative electrode. It "poisons" the negative active material, which greatly increases the spontaneous development of hydrogen there. This increases the self-discharge of the negative electrodes and water consumption if overcharged. Overall, this causes the capacity to be constantly reduced throughout the duration of use. The battery does not achieve the required state of charge, and the electrolyte has to be checked at frequent intervals.

This is why, for grids, lead antimony alloys (PbSb) with a low percentage of antimony by mass are generally still used only for battery types for which regular maintenance is accepted.

Calcium, tin and silver

Today, calcium, tin and silver are usually standard alloying elements for maintenance-free batteries, because they do not noticeably affect hydrogen development, even when released due to corrosion. To ensure the required strength, terminal posts are made from lead alloys with up to around 10 percent of antimony by weight.

Lead-calcium alloys (PbCa) with around 0.1 percent calcium by weight are usually used for negative grids during any manufacturing process. To ensure the required strength, terminal posts are made from lead alloys with up to around 10% antimony by mass.

Lead-calcium alloys (PbCa) with around 0.1% calcium by mass are usually used for negative grids during any manufacturing process. Due to the increased percentage of tin (0.5 to 2%), these alloys feature very high corrosion resistance, which allow lower grid weights.

Casted positive grids are often made from a lead-calcium-silver alloy (PbCaAg). In addition to 0.06% calcium and tin by mass, this alloy also contains a proportion of silver (Ag). It has a finer grid structure and has proved to be extremely durable even at high temperatures – which have the effect of accelerating corrosion.

Charging and discharging

Chemical reactions

The active materials of the lead storage battery include the lead dioxide (PbO_2) of the positive electrode, the sponge-like, highly porous lead (Pb) of the negative electrode and the electrolyte, and diluted sulfuric acid (H_2SO_4). The electrolyte fills the pores of the active materials and the separator and is simultaneously an ionic conductor for charging and discharging. Compared with the electrolyte, PbO_2 and Pb adopt typical electrical voltages (individual potentials). Their difference is equal to the cell voltage of approximately 2 V (at rest) measurable from the outside (Figure 3).

When the cell discharges, PbO_2 and Pb combine with H_2SO_4 to form PbSO_4 (lead sulfate). This conversion causes the electrolyte to lose SO_4^{2-} (sulfation) ions, and its specific gravity decreases. During the charging process, the active materials PbO_2 and Pb are reconstituted from PbSO_4 , H_2SO_4 is released and the electrolyte density increases again (see Electrochemistry, lead battery).

When a discharge current is applied to the battery, this reduces the battery voltage depending on the magnitude of current and the duration of discharge (Figure 4). Therefore, the charge quantity that can be drawn from the battery decreases when the current level increases.

Behavior at low temperatures

The chemical reactions in a battery always take place more slowly at lower temperatures and when internal resistance is increasing. The voltage at the specified discharge current and, therefore, the starting power of a fully charged battery decreases as the temperature drops. The further the discharge progresses, the more the concentration of acid drops, up to the freezing point of the electrolyte. A discharged battery can only supply a low current which is not sufficient to start the vehicle.

Figure 3: Electrical parameters inside and on the battery

I_E Discharge current,
 R_i Internal resistance,
 R_V Load resistance,
 U_0 Steady-state voltage,
 U_K Terminal voltage,
 U_i Voltage drop across internal resistance.

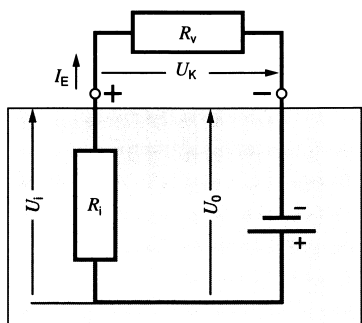
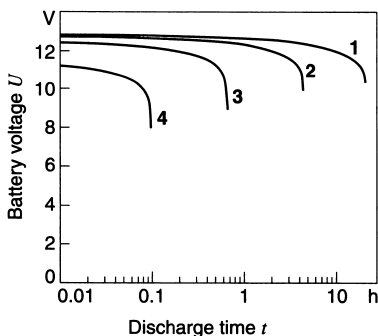


Figure 4: Battery-voltage curves as a function of the discharge duration for various discharge currents

1 $I = 0.05$ A per Ah,
 2 $I = 0.2$ A per Ah,
 3 $I = 1.0$ A per Ah,
 4 $I = 4.0$ A per Ah.



Battery characteristics

In addition to mechanical parameters, such as physical dimensions, attachment, and terminal design, characteristic electrical ratings are defined in testing standards (e.g. DIN EN 50342, [1], [2], [3]). General terminology on batteries is described in DIN 40729 [4].

For the cross-manufacturer marking of starter batteries, a nine-digit ETN (European Type Number) was described in the appendix of the revised EN 50342-1:2001 to compile the most important properties of a starter battery (including voltage, nominal capacity, cold cranking performance, terminal details, etc.). However, this representation cannot map expanded differences regarding construction characteristics, design and areas of application, which are described additionally in requirements outside of EN 50342-1. Therefore, starting with the version from 2006, the ETN nomenclature was withdrawn as a standard in coordination with battery manufacturers and users. Since then, the ETN only continues to be used occasionally.

Capacity

Capacitance is the charge quantity in ampere hours (Ah) which can be drawn from the battery under specified conditions. It decreases as discharge current increases and temperature decreases.

Nominal capacity

EN 50342-1 defines the nominal capacity K_{20} as the charge the battery is able to deliver within 20 h up to a cutoff voltage of 10.5 V (1.75 V per cell) at a specified, constant discharge current $I_{20} = K_{20}/20$ at 25°C. Nominal capacity is calculated from the quantities of active material used (positive material, negative material, electrolyte), and is only marginally affected by the number of electrodes.

Low-temperature test current

The low-temperature test current I_{CC} indicates the battery's current output capability at low temperatures. According to EN 50342-1, the battery terminal voltage with I_{CC} at -18°C must be at least 7.5 V (1.25 V per cell) up to 10 seconds after discharging has started. Further details relating to the discharge period are specified in EN 50342. The short-term response of the battery when discharged at I_{CC} is largely determined by the number, geometric surface area of electrodes, the gap between electrodes, and the separator thickness and material.

The battery internal resistance R_i and other resistances in the starter circuit determine the cranking speed of the engine and also identify the starting response. For a charged battery (with 12 V), R_i at -18°C is in the order of magnitude of $R_i \leq 4,000/I_{CC}$ (in mΩ), where I_{CC} must be applied in amps.

Water consumption

Lead battery loses water from the electrolytes through electrolysis, particularly when charging. EN 50342-1 defines the test conditions for quantification. A limit value of water consumption of 1 g/Ah, for example, means that, under test conditions, a battery with a 50 Ah nominal capacity may lose up to 50 g of water. By comparison, the electrolyte of this kind of battery in new condition, depending on type, contains approximately 1.8 to 2.7 kg of water.

Cycle stability

Lead batteries undergo a certain amount of aging during repeated charging and discharging. EN 50342-1 defines the test conditions for quantification.

Battery types

Maintenance-free battery in accordance with EN

Whether batteries require maintenance by refilling with water depends primarily on the grid alloy used. Batteries with lead antimony alloy (conventional and low-maintenance batteries) are very durable in cyclical charging and discharging operations, but require frequent maintenance because of the high degree of water loss and, therefore, are only used in some commercial vehicles.

Longer maintenance intervals result from low-maintenance batteries with negative grids made from a lead-calcium alloy (PbCa) and positive grids from an antimony alloy (PbSb). However, due to the antimony content in the positive grid, these hybrid batteries also seldom meet the high demand for very low water consumption (in accordance with EN 50342-1, less than 1 g/Ah). Batteries with a water consumption under 4 g/Ah in accordance with EN 50342-1 are considered maintenance-free in accordance with the EN standard.

Completely maintenance-free battery

Both grids in completely maintenance-free batteries are made from the lead-calcium alloy. When the vehicle electrical system is operating normally, this water decomposition is reduced to such an extent (in accordance with EN 50342-1, less than 1 g/Ah) that the electrolyte reserves will last for the entire service life of the battery. Therefore, completely maintenance-free batteries do not require electrolyte level monitoring and do not usually provide a facility for doing this. They have a safety labyrinth cover that prevents electrolyte from escaping even when the battery is at a strong slope and are tightly sealed with the exception of two ventilation openings.

Completely maintenance-free batteries are already filled with electrolyte in the manufacturer's plant and can be stored in a fully charged state for up to 18 months after delivery due to the very low self-discharge.

A "dry" storage without electrolyte occurs only for very few designs (particularly for motorcycles). The electrolyte is first poured in from a delivered acid pack when commissioning in workshops or at dealers' locations.

AGM battery

AGM (Absorbent Glass Mat) batteries are often used for applications with high charging capacities. In these batteries, the electrolyte is bound in a microporous glass-fiber fleece, which, instead of the conventional separators, is located between the positive and negative electrodes (Figure 5).

"Fixing" the electrolyte prevents, for example, the sulfuric acid of high concentration and density released during the charge from sinking and accumulating in the lower area of the cell. This "acid layer" with excess H_2SO_4 in the lower cell area and a shortage in the upper cell area occurs gradually during repetitive charging and discharging in conventional lead storage batteries with freely moving electrolyte. This impairs the charging behavior, accelerates the coarsening of the $PbSO_4$ discharge product's crystalline structure (sulfating), reduces the storage capacity and accelerates the overall aging process of the battery.

In AGM batteries, these effects are reliably prevented. The elastic fleece also slightly pressurizes the electrode pair. This reduces the shedding and separation effect of the active material considerably. Overall, this enables charging capacities more than three times higher than in comparable starter batteries with free electrolyte by charging and discharging throughout the entire service life. This makes it particularly well-suited for vehicles with a start/stop system that require the consumer to be supplied when the engine is stopped and then restarted reliably. Other typical cases of application for AGM batteries include vehicles with many electrical consumers that are also used when the vehicle is stationary (e.g. auxiliary heater, consumer electronics), taxis, special vehicles and logistics vehicles.

In the AGM battery, the oxygen that occurs at the positive electrode in an internal circuit is used up again, the amount of hydrogen that is produced there is suppressed and the amount of water loss is therefore minimized further. This circuit is enabled by small gas channels in the separator fleece, through which the oxygen is transported. The individual cells are separated from the environment by valves that open only if the operation causes the internal pressure to exceed a value of approximately 100 to 200 mbar. Under normal operating conditions, the valves are closed, which reduces water consumption even further. Lead batteries with sealed valves, such as the AGM battery, are called VRLA batteries (Valve Regulated Lead Acid Battery) and are completely maintenance-free.

The inner resistance is particularly low and high cold start currents are achieved because of the high porosity of the glass-fiber fleece. Therefore, AGM batteries are also often used in diesel vehicles.

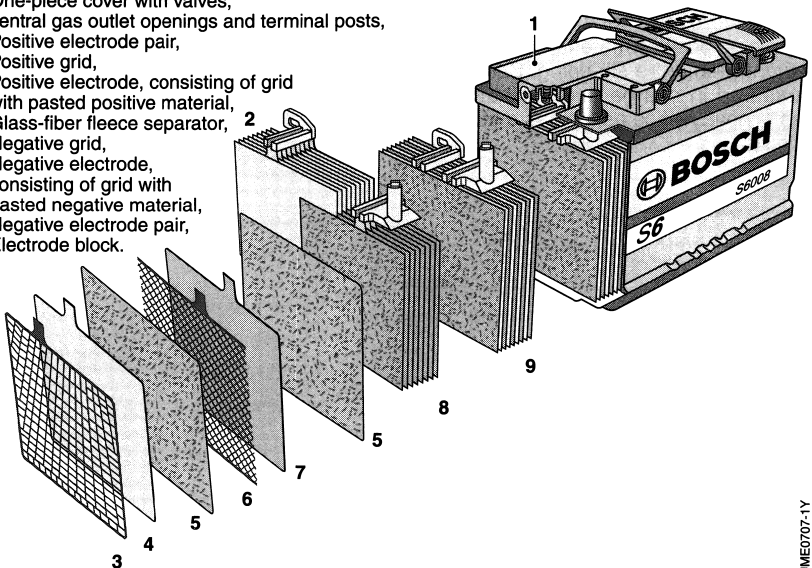
Even if the battery housing is destroyed (e.g. in case of an accident), the electrolyte bound in the glass-fiber fleece (diluted sulfuric acid) does not generally leak. This and the improved gassing characteristics make the AGM battery particularly well-suited for installation points in the passenger cell.

EFB battery

The EFB battery (Enhanced Flooded Battery) is a battery with free electrolyte optimized for use in vehicles with a start/stop system. Although an acid layer is also formed when cyclic charging batteries without fixed electrolyte, such as the AGM battery. However, the positive plates coated with polyester scrim, which provide additional support of the active material, and further design features produce a more robust design and a greater deep-cycle resistance in comparison with standard batteries.

Figure 5: AGM battery

- 1 One-piece cover with valves, central gas outlet openings and terminal posts,
- 2 Positive electrode pair,
- 3 Positive grid,
- 4 Positive electrode, consisting of grid with pasted positive material,
- 5 Glass-fiber fleece separator,
- 6 Negative grid,
- 7 Negative electrode, consisting of grid with pasted negative material,
- 8 Negative electrode pair,
- 9 Electrode block.



Commercial vehicle batteries

Bosch also provides completely maintenance-free batteries for commercial vehicles. Specifically in commercial vehicle applications, these batteries offer a substantial cost advantage. These battery types have a special labyrinth cover, which guarantees leakproof performance and features central venting. Porous frits integrated into the outlet opening prevent flames or sparks outside from backfiring into the inside of the battery. There are special design variations for applications with extreme cycle or vibration stress.

The housing dimensions of commercial vehicle batteries are described in the standard EN 50342-4.

Deep-cycle resistant battery

Due to their design (relatively thin electrodes, lightweight separator material), starter batteries are less suitable for applications which involve repeated exhaustive discharging, as this results in heavy wear on the positive electrodes (mainly caused by a loosening and shedding of active materials). A deep-cycle resistant starter battery has separators with glass mats that support relatively thick plates containing positive material and therefore prevent premature shedding. Service life measured in charge and discharge cycles is nearly twice as long as a standard battery.

Vibration-proof battery

In a vibration-proof battery, the plate block is fixed to the battery case by means of cast resin or plastic to prevent any relative movement between the two components. In accordance with DIN EN 50342-1, this battery type must pass a 20-hour sinusoidal vibration test (at a frequency of 30 Hz) and be capable of withstanding a maximum acceleration of 6 g. Requirements are therefore about 10 times greater than for standard batteries.

Vibration-proof batteries are mainly used, for example, in commercial vehicles, construction machines or tractor vehicles.

Heavy-duty battery

A heavy-duty battery combines the attributes of the deep-cycle resistant and vibration-proof types. It is used in commercial vehicles which are subjected to extreme vibrations, and where cyclic discharge patterns are commonplace.

Battery for extended current output

This battery type shares the basic design of a deep-cycle resistant unit, but has thicker and fewer electrodes. Although no low-temperature test current is specified, the starting power lies well below (35 to 40%) starter batteries of the same size. This battery type is used during extreme cyclic charges, sometimes for driving purposes as well.

Using the battery

Charging

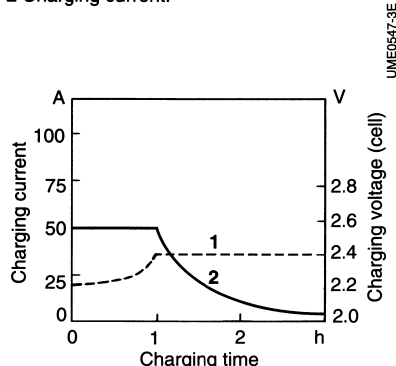
In vehicle electric systems, the alternator regulator specifies the voltage. In terms of the battery, this corresponds to the *IU*-charging method, where the battery charge current *I* is initially limited by the output of the alternator and then reduces automatically if the battery voltage reached the control value (Figure 6). Since the current consumption capacity of the battery decreases at low temperatures, the charge voltage in the vehicle is usually regulated depending on the temperature (Figure 7). At battery temperatures well under 0°C, current is consumed only very slowly.

The *IU* charging method prevents damage due to overcharging, and makes sure that the battery has a long service life. Modern battery chargers operate according to similarly defined characteristic curves.

Older devices, on the other hand, still operate using constant current or a *W*-characteristic curve. In both cases, once the full state of charge has been reached, charging continues with only a slightly reduced current, or possibly a constant current. This leads to high water consumption and to subsequent corrosion of the positive grid. In particular, maintenance-free batteries can be damaged by this in the long term.

Figure 6: Charging according to the *IU* characteristic

1 Charge voltage,
2 Charging current.



Discharging

Shortly after discharging at a continuous current begins, the voltage in the battery drops to a value which only changes relatively slowly if discharging continues. Only shortly before the end of the discharging process will the voltage collapse sharply due to exhaustion (d.h. complete electrochemical implementation) of one or more of the active components (positive or negative material, electrolyte).

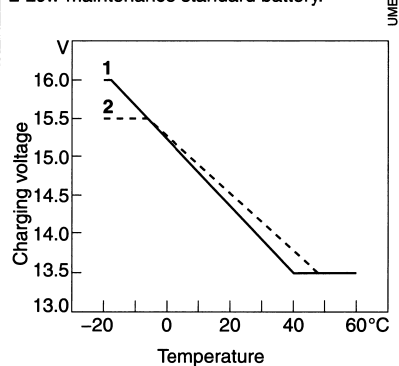
Self-discharge

Batteries discharge over a period of time if no electrical equipment is connected. Causes include the spontaneous development of oxygen at the positive electrode and hydrogen at the negative one, as well as the continuously expiring slow corrosion of the positive grid. Completely maintenance-free batteries with lead calcium grids have a self-discharge of approximately 3% per month at 25°C, which remains roughly constant over the entire service life and nearly doubles for each temperature increase of 10 degrees.

Modern batteries using the lead-antimony alloy lose approximately 4 to 8% of their charge every month when new. As battery ages, this value can increase by up to 1% or more each day due to the migration of antimony to the negative electrode until a point is reached when the battery finally stops functioning.

Figure 7: Temperature-dependent charging characteristic

1 AGM battery,
2 Low-maintenance standard battery.



Battery maintenance

On low-maintenance batteries, the electrolyte level should be inspected in accordance with the manufacturer's operating instructions; when required, it should be replenished to the MAX mark with distilled or demineralized water. This is generally not required for maintenance-free batteries in accordance with EN standard. This step is omitted entirely for completely maintenance-free batteries.

All batteries should be kept clean and dry to minimize self-discharge. Terminal posts, terminal clamps, and fixings should be coated with acid-protection grease.

Before the onset of winter, it is recommended to check the battery status with a modern battery tester. If this tester recommends recharging, the battery should be recharged at a maximum voltage of approximately 14.4 to 14.8 V with a suitable charger with a regulated charging characteristic curve (*IU* charging characteristic curve or similar to prevent overcharging). Here, note the information in the user manual for the vehicle, battery and charging device. The charging area should be well ventilated (risk of explosion due to oxyhydrogen gas, risk of explosion, no naked flames or sparks). The electrolyte is corrosive. Therefore, gloves and protective eyewear must be worn when handling.

If no battery tester is available, a measurement of the electrolyte density or – if not possible – the steady-state voltage as a replacement. The battery should be recharged as described above if the electrolyte density is under approximately 1.24 g/ml or the steady-state voltage is under approximately 12.5 V.

Batteries temporarily removed from service should be stored in a cool, dry place. If the above-mentioned criteria exist, recharging is also required. Long service lives at a low state of charge increase grid corrosion and reinforce sulfating. During this, the finely crystalline lead sulphate transforms into roughly crystalline, which makes the battery more difficult to recharge. These effects gradually damage the battery and can lead to their failure in the long term.

Battery malfunctions

Functional disturbances due to damage inside the battery cannot be remedied through repair. The battery has to be replaced.

A battery failure usually does not happen abruptly; instead, steadily decreasing starting power can provide an indication of the problem. Causes usually include a combination of consumed or sulfated active materials, grid corrosion and short-circuits due to separator wear. Modern battery testers can be used to evaluate whether a weak battery needs to be replaced or can simply be recharged.

If no battery defects are determined and the battery's charge is still always low, there may be a fault in the vehicle electrical system (defective alternator, electrical consumers remain switched on when the motor is not running, etc.). The battery can also be insufficiently charged as a result of using the vehicle primarily for short-distance driving. This can be balanced by occasionally driving longer distances or, alternatively, by occasionally recharging with an external charging device.

Battery testers

The starter battery is a wearing part. The service life is heavily dependent on the type and use of the vehicle and the climatic conditions. Aging becomes noticeable due to an increase in the internal resistance R_i (which impedes the start performance) and a reduction of the storage capacity by loosening of the active materials or sulfating. A low state of charge, on the other hand, is not a characteristic of aging, but a consequence of a usage with insufficient charge balance.

Often, a quick evaluation of the state of an older starter battery is desired, for example, to decide whether recharging is sufficient or a replacement is required. To do so, battery testing devices are available that can be connected to the powered-down battery and make a statement after a test duration of generally less than a minute.

Usually, these testing devices imprint a certain current charge profile onto the battery and deduce the battery state from

the voltage response. To do so, they use partially simplified electrochemical impedance spectroscopy approaches (EIS, see electrochemical impedance spectroscopy). In general, the battery's correlation to the steady-state voltage is used to estimate the state of charge. Therefore, the battery must not be charged with other currents during the test.

Either a very rough evaluation (e.g. "ok", "charge", "replace", "test again") or a quantifying specification (e.g. "state of charge 82%", "startability 87%") is given, depending on the design of the tester. Different manufacturers use a wide variety of methods.

Often, nominal values of the battery (capacities, cold cranking performance) must be specified and relative evaluations are made. The battery design (free electrolyte or AGM) and the battery temperature are also often requested or measured directly to also take into account this important influencing factor.

Battery testers cannot replace a complete test according to the applicable standards (e.g. EN 50342-1), but instead quickly give guideline for additional actions for batteries that have been in use for an extended amount of time. This test is not valid for new or like-new batteries because the structure of the active materials is often not yet balanced immediately after manufacturing.

Replacing the battery

Specifications in the vehicle's operating instructions must be taken into account when replacing batteries. These operating instructions often describe the specified or permissible sizes and design. The replacement battery should at least provide the specified capacity and cold cranking values to ensure functional and operational reliability. If a special battery design, such as AGM or EFB, is specified, such as in vehicles with a start/stop system, a replacement battery of the same design must be used.

References

- [1] EN 50342-1:2006 + A1:2011: Lead-acid starter batteries – Part 1: General requirements and methods of test.
- [2] EN 50342-2:2007: Lead-acid starter batteries – Part 2: Dimensions of batteries and marking of terminals.
- [3] EN 50342-4: 2009: Lead-acid starter batteries – Part 4: Dimensions of batteries for commercial vehicles.
- [4] DIN 40729:1985: Accumulators; Galvanic Secondary Cells; General Terms And Definitions.

Drive batteries

Requirements

The drive battery in modern electric vehicles often accounts for more than two-thirds of the weight, size and cost of all components in the electric powertrain. Therefore, the main challenge for the future is to improve and optimize the battery in terms of these three criteria.

A drive battery, also called the battery pack, consists of many battery cells. The (sometimes conflicting) requirements described below must be taken into account when developing and designing the cells and other components in the battery pack.

Safety

The safety of vehicle occupants and the environment must be guaranteed in all situations. This applies to hazards that result from the electrochemical properties of the battery, for example, preventing fire. It must also take electrical safety into account, particularly in batteries with voltages larger than 60 V.

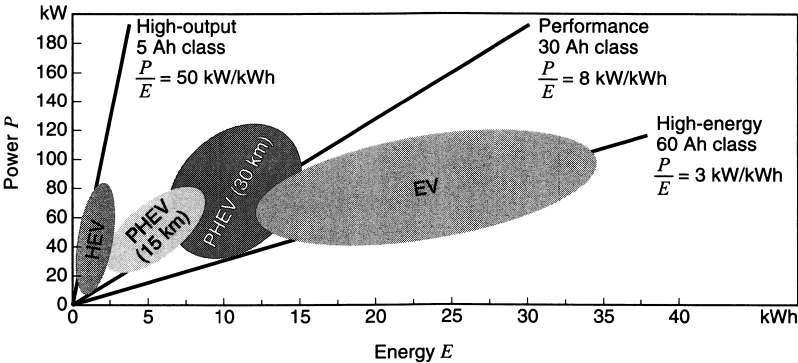
Performance

For use in vehicles, low weight and high performance are required simultaneously. Achieving this requires batteries with high energy and power density. There are different requirements for this depending on the vehicle. Figure 1 shows the typical values for the respective characteristics and the ratio of performance *P* to energy *E*. This results in various requirements for the battery cells used. Various cell sizes and designs are required to be able to cover all vehicle segments.

Operation in the automotive sector requires a service life usually lasting more than ten years or a running performance of typically 250,000 km. In purely electric vehicles, approximately 3,000 complete charging cycles occur throughout the life of the vehicle, while hybrid applications often have over a million partial charging cycles. The largest challenge by far is to reduce the costs with the goal of reaching total costs comparable to those in systems with internal-combustion engines.

Figure 1: Requirements for energy content and capacity of the battery for various vehicle concepts

HEV Hybrid Electric Vehicle,
PHEV Plug-in Hybrid Electric Vehicle,
EV Electric Vehicle.



Storage technologies

Today, lithium-ion (Li-Ion) batteries are usually used as electrical energy accumulators in electric vehicles, hybrid vehicles and plug-in hybrid vehicles. Nickel-metal hydride batteries (NiMH) are still used in isolated cases. However, it is to be expected that these will be gradually replaced by lithium-based battery systems.

Figure 2 shows a comparison of specific output and specific energy of various technologies.

Nickel-metal hydride technology

Nickel-metal hydride batteries have already been in use as drive batteries for a few years, in particular for hybrid vehicles. The primary disadvantage of cells in nickel-metal hydride technology, however, is the lower energy density at a specific power that is also usually lower compared to lithium-ion batteries. Nickel-metal hydride cells achieve a specific energy of up to 80 Wh/kg at a voltage of typically 1.25 V per cell. Nickel-metal hydride cells also have higher self-discharge than lithium-ion cells.

Lithium-ion technology

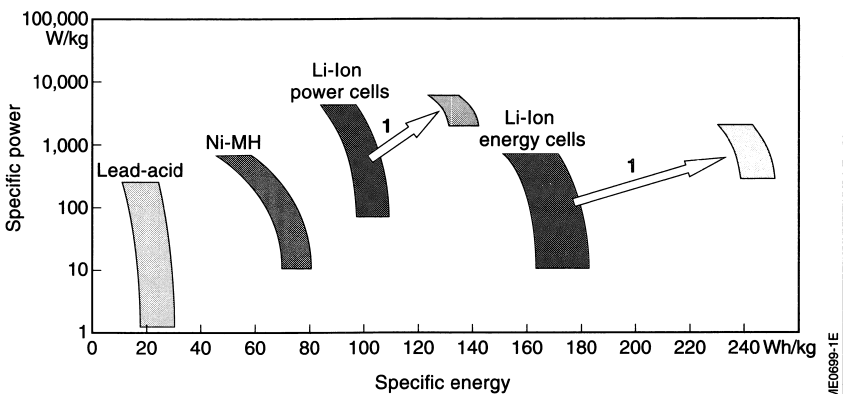
Lithium-ion systems feature a rated voltage of approximately 3.7 V per cell, while the voltage limit in use is between 2.8 V and 4.2 V.

The positive electrode (cathode) of a lithium-ion cell is based on a metal oxide structure that can store lithium ions (see Electrochemistry). These metal oxides – the active material – currently usually consist of compounds from nickel, manganese or cobalt. The lithium ions move around in a reversible mechanism during the discharging process towards the negative electrode (anode) and during the charge operation towards the positive electrode (cathode). Graphite is frequently used as the active material in the anode.

New materials are in development in order to improve safety characteristics and increase the energy and power density. This includes, for instance, using lithium iron phosphate (Li_xFePO_4) in the cathode or lithium-titanate oxide ($\text{Li}_4\text{Ti}_5\text{O}_{12}$) in the anode instead of graphite.

Figure 2: Attainable specific energies and capacities for various storage technologies (Ragone chart)

1 Development goal for the year 2020.



The simultaneous optimization to a high output and energy density is a technical challenge. A high power density requires large electrode surfaces with low-resistance conductors, while a high energy density requires the opposite: compact electrodes with a large amount of active material.

Typical characteristic values of today's automotive cells include 5,000 W/kg for the specific performance of power cells and 180 Wh/kg for the specific energy of energy cells. Lithium-ion systems with a high specific energy of 250 Wh/kg are in development (see Figure 2).

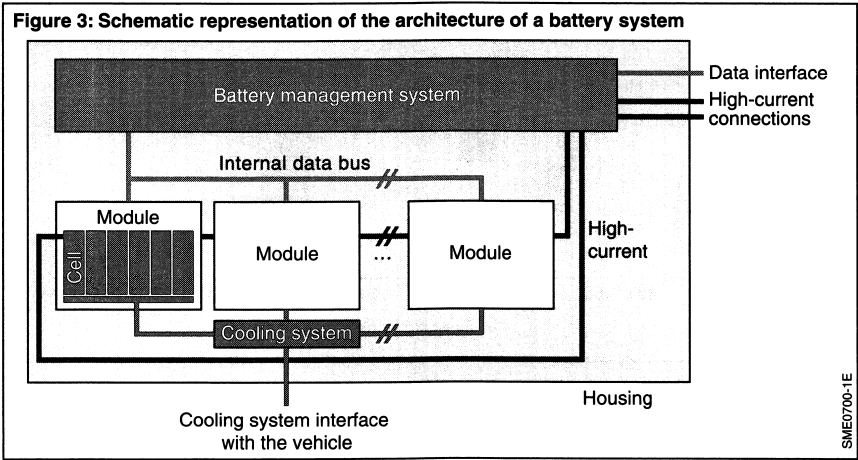
Lithium-ion systems, compared to other technologies, require more elaborate system monitoring and control systems using a battery management system. A lithium-ion battery must be kept within strictly defined charge, current and temperature limits for service life and safety reasons. In particular, lithium-ion cells are not capable of tolerating overcharging. Monitoring electronics are used to prevent this.

It is to be expected that cells based on innovative electrochemical approaches, such as lithium-sulfur or lithium-air, are able to provide significantly higher energy and power densities at equal or even lower costs. However, systems based on this are still being researched. The capability for mass production for use in the automotive industry has yet to be proven.

Basic structure of a battery system

Drive batteries also differ in their internal structure due to each of the different technical requirements and individual installation situations in the vehicle. However, most follow a similar basic concept, which is depicted below.

A battery system usually consists of multiple modules, each of which, in turn, contains multiple cells. The modules are connected to each other via a high-voltage wiring harness and are integrated together with the battery management system and cooling system in a battery housing. Interfaces for the vehicle include the high-voltage terminals of the battery, a data interface and usually an additional connection for the cooling system (Figure 3).



Components of a lithium-ion battery system

Lithium-ion battery cells

Depending on the application, a drive battery consists of battery cells, ranging from ten to one hundred and, in individual cases, even thousands. Here, battery cells are used in three different designs (shown in Figure 4) for use in automotive industry.

Designs

Battery cells with cylindrical metal housing have major cost advantages in manufacturing when compared to the other designs.

Prismatic cells with a housing made of laminated metal foil (pouch cells) have a particularly homogeneous temperature distribution and permit highly compact battery systems of flexible sizes.

Prismatic hardcase cells also permit a very compact construction and are

also pressure-sealed and stable in comparison.

It is still uncertain whether one of the three cell types will prevail for automotive applications. Currently, there is an identifiable trend toward pouch cells and prismatic hardcase cells.

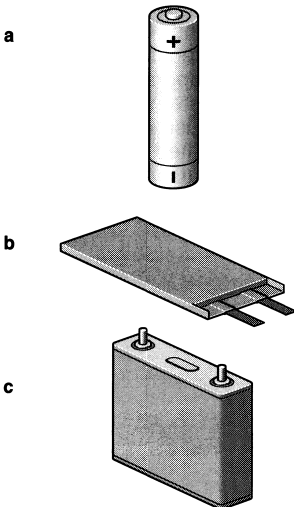
There are global efforts to standardize the types of cell housing for automotive applications as well.

Layout of a lithium battery cell

Figure 5 shows the cross-section of a prismatic hardcase cell. The active materials required for the chemical process in the anode (for example graphite) and the cathode (lithium compound) are present as coating on a copper film (anode) and an aluminum film (cathode). The metal films are each used here as shunts. The films, coated on both sides, are separated by a separator film that prevents a direct electrical connection between the anode

Figure 4: Lithium-ion battery cell designs

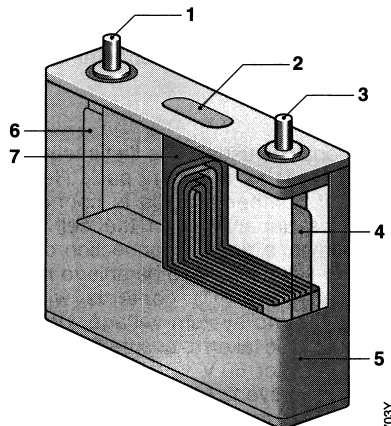
- a) Battery cells with a cylindrical metal case,
- b) Prismatic cells with case made of laminated metal foil,
- c) Prismatic hardcase cell.



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Figure 5: Cross-section of a prismatic hardcase cell

- 1 Positive terminal (pole),
- 2 Safety valve,
- 3 Negative terminal (pole),
- 4, 6 Shunts,
- 5 Cell case,
- 7 Cell winding with anode, cathode and separator.



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and cathode, but is conductive for ions. The ion-conductive electrolyte is also located between the anode and cathode. This sequence of anode, cathode and separator is wound into a flat coil of cells, the electric shunts at the anode and cathode lead to the negative/positive electric terminal of the cell.

An additional safety valve is also located on the cell. If the pressure in the cell rises in the case of a malfunction, it opens to prevent the cell from bursting.

Safety requirements

When a technology-dependent temperature threshold in the cell (typically around 140°C) is exceeded, a self-reinforcing, irreversible exothermic process called "Thermal Runaway" starts and can no longer be stopped by external influences. This can cause the cell to start on fire or burst. Therefore, corresponding measures must be taken to ensure that this process is not triggered by improper operation.

Mechanical and electric components

Battery cells have to be interconnected in a suitable form and mechanically integrated for use in vehicles. This accounts for the mechanical and electrical safety requirements that are particularly applicable for batteries with high voltage. Typical automotive industry requirements also apply here, both in use (such as vibration protection or splash water) and in potential cases of malfunction (e.g. protecting occupants and the environment in case of an accident).

Module

The module is usually the first integration level of cells for a battery pack. Here, a different number of cells is connected in series depending on the cell type. Sometimes, a parallel connection of two or more cells is used to be able to represent larger energy contents without increasing the system voltage. Usually, care has to be taken to ensure that a module voltage of 60 V is not exceeded in order to prevent high-voltage requirements at the module level.

The cells are mechanically integrated into a network and their terminals are connected by a high-voltage cable harness. Additionally, sensors and evaluation electronics are frequently integrated into the module. The focus here is to ensure the most compact design engineering possible that allows flexible, cost-effective and high-quality battery production.

While small battery systems can only consist of one module, battery packs for electric vehicles often use over ten modules. The modules are connected to each other electrically via a high-voltage cable harness.

Housing

The battery housing, along with holding together the cells and protecting them from mechanical loads, is also used for contact protection against high voltages. On the outside of the battery housing, there are high-voltage connections for connecting to the electric powertrain, a communication interface for data exchange with the higher-level vehicle control unit for the electric drive (e.g. engine management system) and, in many places, interfaces for the cooling system.

Battery management system

Determining characteristics of the battery system, complying with the permissible operating limits and regulating the cooling system are necessary for safe and reliable battery operation. The battery management system (BMS) assumes these tasks. It is usually implemented in a control unit located inside the battery. However, individual functions can also be assumed by external control units.

Operation

The battery management system measures the battery current, the temperature of the battery cells and the voltage of individual cells, the voltage of individual modules and the voltage of the overall battery. This is used to determine the battery cells' state of charge (SOC) and state of health (SOH). The currently available battery rating and permissible battery current can be determined based on this. The battery management system can also carry out "Balancing" to match the cells' state of charge. This information is transmitted to the central vehicle control unit in the electric powertrain of the vehicle. The battery management system cannot directly affect the discharge current, charging current and state of charge during this process. The vehicle control unit controls the power electronics in the electric powertrain or the charging device based on the information sent by the battery management system to configure a corresponding current.

The battery management system protects the battery cells by preventing the current flow in cases when the battery is overcharged, the safe operating window is exited due to over- or undervoltage, or if the battery is overheated. This occurs by instructing consumers to switch off the vehicle control unit in case of emergency by disconnecting the battery on its own.

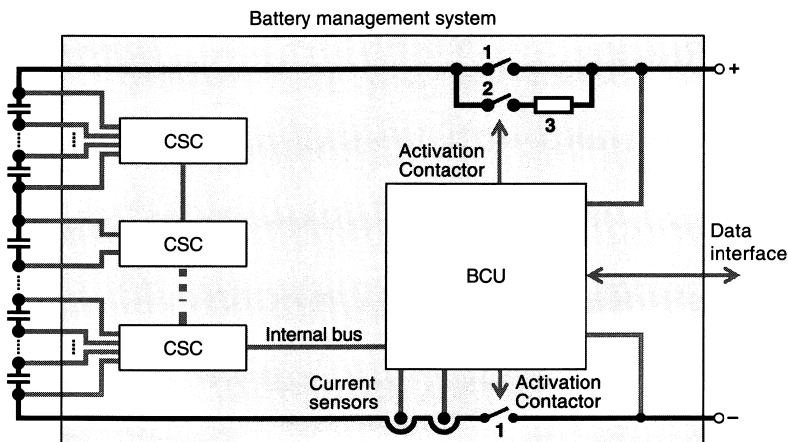
Even if the battery itself has to be assigned to the electrochemical domain, the functional safety standard (ISO 26262 [1]) for electrical and electronic components must be taken into account when developing the battery's safety concept for the battery management system. Safety-related components of the battery management system, particularly the sensor technology, are, therefore, redundant.

Architecture

In Figure 6, the distributed architecture of a battery management system for plug-in hybrid electric vehicles (PHEV) and electric vehicles (EV) is shown as an example.

Figure 6: Overview of the battery system

- 1 Main contactor,
 - 2 Charging contactor,
 - 3 Pre-charging resistor.
- CSC Cell Supervisory Circuits,
BCU Battery Control Unit.



Other architecture variants are also used, particularly for hybrid electric vehicles (HEV).

The battery management system consists of a central battery control unit, cell supervisory circuits, current sensors and a contactor circuit. The cell supervisory circuits monitor the battery cells in terms of their voltage and temperature.

Manner in which current is conducted
The contactor current allows the vehicle electrical system battery of the electric powertrain to be electrically isolated. If an accident is detected or another potential hazardous state is identified, a control logic opens the contactor that is located at each positive or negative battery terminal. To prevent a safety-critical condition, this logic can open the contactor even if the battery system is overloaded.

The battery is connected to the vehicle electrical system of the electric powertrain with its buffer capacitor via a charging contactor and a pre-charging resistor. This prevents an excessively large initial charge current when the buffer capacitor is discharged. During normal operation, the battery is connected to the vehicle electrical system with low impedance via the main contactor.

Balancing

Due to manufacturing tolerances and side reactions that depend on cell parameters and the cell temperature, the individual cells eventually have a different state of charge. This is problematic insofar as the cell with the lowest state of charge sets the discharge limit, and the cell with the highest state of charge sets the charge limit. For this reason, the state of charge of a battery's cells has to be balanced from time to time. This is done by a balancing circuit, which is usually integrated in the cell supervisory circuits. In automotive applications, balancing is typically a passive process; that is, it occurs by discharging individual cells via a resistor connected in parallel.

Thermal management

To ensure safe and reliable operation of the battery even when the load is fluctuating and to maximize the service life of the cells, the temperature of the cells should be kept in a range typically from 20 °C to 40 °C. The service life of the battery cells is largely reduced as the temperature increases, because many aging processes are temperature-dependent. This is particularly relevant for use in hot climate zones. At low temperatures, the capacity of the cells noticeably decreases.

In vehicles, there are various systems used to control the temperature of cells.

Liquid-cooling system

Liquid-cooling systems are usually used in systems with high requirements for regulating temperature. The battery is equipped with a separate cooling circuit, in which circulates a special coolant, such as a water-glycol mixture. The coolant temperature is controlled by a heat exchanger, which is connected to the vehicle's air-conditioning system. Frequently a heater element is also integrated, so that the battery can be heated at low temperatures.

It is connected to the battery cells via cooling plates. Temperature sensors monitor the temperature of the cells. The central thermal management system, often integrated in the battery management system, controls the flow rate and coolant temperature depending on the situation and temperature.

Batteries with a liquid-cooling system can be built very compactly, but require additional effort due to the cooling plates, the piping and the connection to the vehicle's air-conditioning system.

Refrigerant cooling system

An alternative to a liquid-cooling system is the refrigerant cooling system, in which the cooling components of the battery are designed as evaporators and directly integrated into the refrigerant circuit of the vehicle's air-conditioning system. Systems of this kind have been used only rarely to date.

Air cooling

Air-cooled systems are the most cost-effective designs. However, they require more space due to the need for space between the cells. Moreover, the air interfaces mean that hermetically sealed battery cases are not possible, or they can be implemented only with great effort.

Air-cooled systems are often used for batteries with low cooling requirements, for example, in systems with low specific power requirements, such as batteries for electric vehicles and for use in moderate climate zones.

In air-cooled systems, fans controlled by a thermal management system take in air that is usually precooled. This is blown through the battery system; the fan speed can be controlled depending on the cell temperature determined by the temperature sensors.

Some systems for low power requirements have no fans; in that case, the battery cells are simply cooled by natural convection.

References

[1] ISO 26262: Road vehicles – Functional safety.

Electric machines

Energy conversion

Electric machines are electro-magneto-mechanical energy converters in motor and generator operation. The supplied electrical energy W_{el}

$$W_{el} = W_m + W_v$$

is converted into magnetic energy W_m and lost energy W_v where

$$W_m = \int_0^{t_0} u_l i_l dt \text{ and } W_v = \int_0^{t_0} i_l^2 R dt.$$

Where $u_l = d\Psi/dt$ the magnetic energy follows by means of integration

$$W_m = \int_0^{\Psi_0} i_l(\delta, \Psi) d\Psi.$$

Here δ is the air gap in the magnetic circuit, Ψ the magnetic flux interlinked with all the turns of a winding, and Ψ_0 the maximum occurring interlinked magnetic flux. In Figure 1 for example the energy W_m is accumulated in the space $V = A_z \delta$ above the tooth surface permeated by the flux Φ . Through discharging of the magnetic energy to a space coordinate Ω the magnetic force F_m follows

$$F_m = \frac{\partial W}{\partial \Omega}$$

in the direction of the space coordinate as a force on the boundary layer for the generation of motion. If, for example, the magnetic energy is discharged to a circumferential coordinate, this results in a magnetic force in the circumferential direction which through multiplication by radius r causes the torque $M = F_m r$. If the magnetomechanical energy conversion is effected through discharging of the magnetic energy to an angular coordinate α , torque M follows:

$$M = \frac{\partial W}{\partial \alpha}.$$

The section of a permanent-magnet motor is shown in Figure 1. The stator consists of the magnetic yoke and the permanent magnet. The rotor is formed by the rotor-tooth surface A_z , the rotor tooth, and

the winding, which is permeated by the magnetic flux and causes a torque-producing reluctance force (tangential force F_t) at the tooth surface. The normal force F_n acting on the tooth surface counterbalances together with the normal force of the opposite tooth on the shaft.

With regard to forces, a distinction is made between the following:

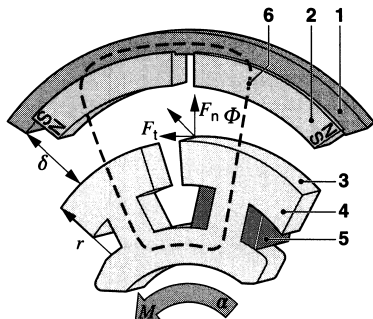
- magnetic force which acts on a boundary layer consisting of air and iron,
- Lorentz force on moving charge carriers in the magnetic field.

Application examples for the first case are commutator machines and switched reluctance motors. Application examples for the second case are commutator machines with ironless rotors and commutator disk-rotor machines.

For further references, see [1] and [2].

Figure 1: Sectional view of an internal-rotor motor

- 1 Magnetic yoke,
 - 2 Permanent magnet,
 - 3 Rotor-tooth surface A_z ,
 - 4 Rotor tooth,
 - 5 Armature winding,
 - 6 Magnetic flux Φ .
- r Rotor radius,
 F_t Tangential force (reluctance force),
 F_n Normal force, M Torque,
 α Angle of rotation,
 δ Air gap in the magnetic circuit.



Systematics of rotating electric machines

The energization of the windings of electric machines determines their properties. A distinction is made between self-commutated (position-commutated, field-commutated) and externally commutated (line-commutated, frequency-commutated) motors.

The first group includes DC motors in which cyclic activation of the winding phases in the rotor is effected on a self-regulated basis via the mechanical (or electronic) commutator. Magnetic excitation is effected either with an electromagnet (DC and AC operation of the motor possible) or by means of permanent magnets (only DC operation of the motor possible).

In externally commutated motors (e.g. asynchronous motor) the phases are switched by the supply system or the control electronics. Table 1 shows a systematization of electric motors with regard to their commutation performance. DIN 42027 [3] sets out motor systematics with regard to power supply.

Definitions of geometric quantities

Figure 2 depicts a 4-pole (number of pole pairs $p = 2$) machine cross-section. The quantities are named in part by DIN EN 60027-4 [4]. This standard gives names and letter symbols for quantities and units.

A pole pair consists in each case of a north pole and a south pole. The magnetic flux that is set emerges from the north pole through the rotor via the air gap into the south pole.

Figure 2: Stator section and rotor section with dimensioning

- 1 Stator,
- 2 Rotor (with radius r_R).
- τ_p Pole pitch ($= \pi d/2p$),
- p Number of pole pairs,
- τ_Q Slot pitch ($= \pi d/Q$),
- Q Number of slots,
- b_L Pole-gap width,
- b_P Pole-shoe width,
- r_S Stator radius,
- δ Air gap,
- Φ Magnetic flux.

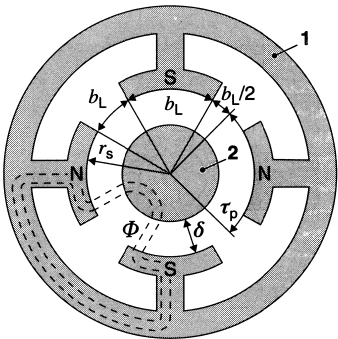
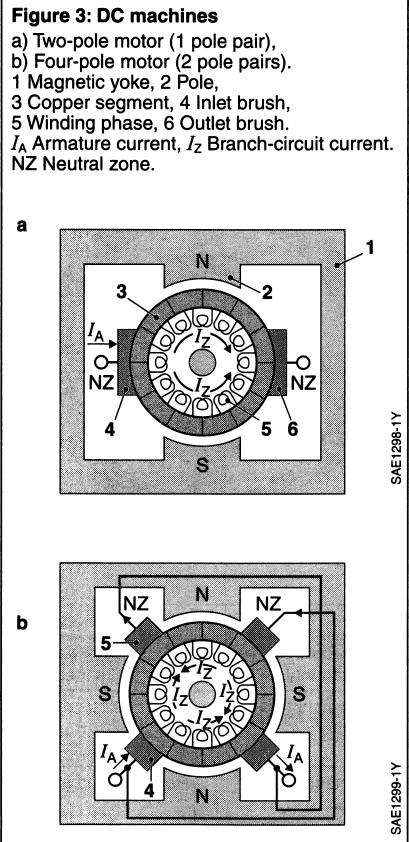


Table 1: Systematics of electric motors

Self-commutated machines		Externally commutated motors	
Mechanical commutator		Load-dependent rotational speed	Frequency-dependent rotational speed
AC motors	DC motors	Asynchronous motors	Synchronous motors
Commutator motors, universal motors	Series-wound, shunt-wound motors	Rotating-field motors, cage motors	Rotating-field motors

Direct-current machines

In direct-current machines motor operation is frequently preferred to generator operation. These are used for example as drives for electric fuel pumps, fans, starters, windshield wipers, and power-window units. Figure 3a shows a two-pole motor and Figure 3b a four-pole motor. In higher-pole motors a number of shorter magnetic circuits are generated which facilitate greater utilization of the magnet volume. The motors consist of the magnetic yoke, the poles, copper segment, inlet brush, winding phase, and outlet brush, through which the armature current I_A passes which in turn is split into the branch-circuit currents I_Z .



Direct-current machines with excitation by electromagnets are classified according to their winding behavior. In a series-wound motor the armature and excitation windings are connected in series. In a shunt-wound motor the armature and excitation windings are connected in parallel. The terminal markings of direct-current machines comply with DIN EN 60034 Part 8 [5] and DIN EN 60617 Part 6 [6].

Commutator voltage

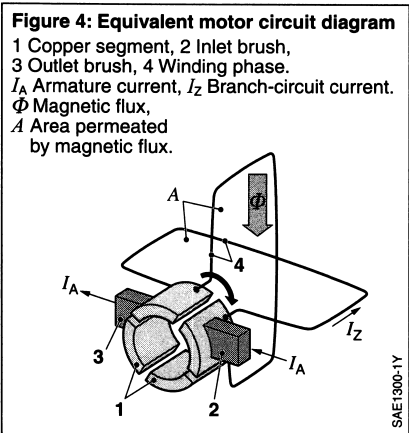
Figure 3 is simplified down to the equivalent motor circuit diagram Figure 4, consisting of commutator and two phases reduced to one turn. The equivalent electric circuit diagram Figure 5 is derived from this. Figures 5a and 5b show motor operation, Figures 5c and 5d show generator operation. The voltage relationships that are obtained can be taken from Table 2.

The induced voltage U_L is according to Faraday's law

$$U_L = \frac{d\Psi(I, \delta)}{dt} \tag{1}$$

With the total differential (differentiation of a function according to all its independent variables) of the interlinked, current- and air-gap-dependent magnetic flux Ψ

$$d\Psi = \frac{\partial \Psi(I, \delta)}{\partial I} dI + \frac{\partial \Psi(I, \delta)}{\partial \delta} d\delta \tag{2}$$



the induced voltage follows again

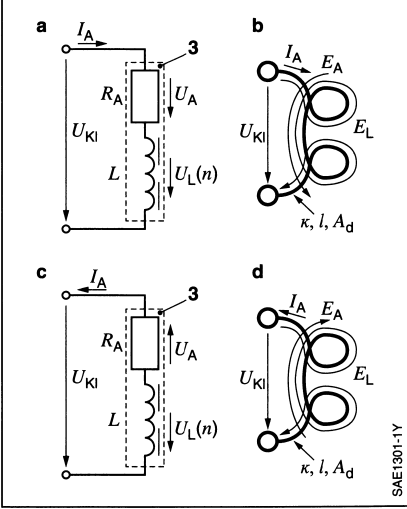
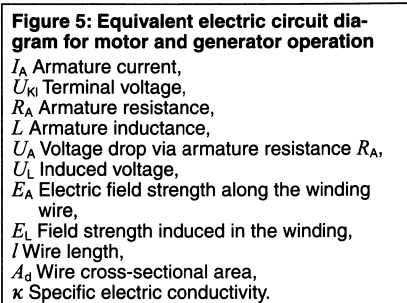
$$U_L = \frac{\partial \Psi(I, \delta)}{\partial I} \frac{dI}{dt} + \frac{\partial \Psi(I, \delta)}{\partial \delta} \frac{d\delta}{dt}, \quad (3)$$

where the first term becomes zero due to DC energization. This leaves the second term of Faraday's law, which is further developed with the number of turns N , the flux Φ , the flux density B , and the area A :

$$U_L = N \frac{\partial \Phi}{\partial \delta} \frac{d\delta}{dt} = NB \frac{dA}{dt}. \quad (4)$$

Table 2: Voltage relationships

Motor operation	Generator operation
$U_{KI} = U_A + U_L$	$U_{KI} = U_A - U_L$
$U_{KI} = E_A I + E_L I$	$U_{KI} = E_A I - E_L I$
$U_{KI} = (E_A + E_L) I$	$U_{KI} = (E_A - E_L) I$



With the replacement of the differential function by a differential function using the period T and taking into account that for the arrangement in Figure 4 with $k = 4$ segments for commutation only $T/4 = T/k$ time remains, the induced voltage follows again

$$U_L = NB \frac{A}{T} = N B A f k \quad (5)$$

as a function of the rotational frequency f [s^{-1}]. An extension with 60 and conversion with $c_1 = k \cdot 60$ leads to

$$U_L = \Psi n k \cdot 60 = L I n c_1 = \Psi n c_1 (n \text{ in } \text{min}^{-1})$$

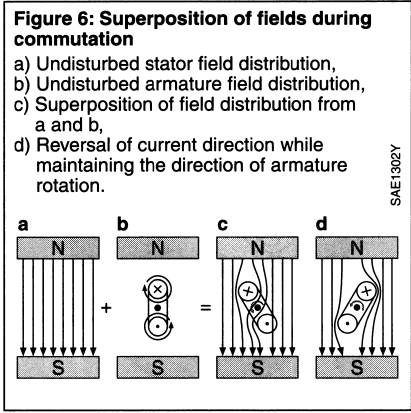
and thus to the rotational-speed-proportional induced voltage with which the mesh equation of Figure 5

$$U_{KI} = R_A I_A \pm \Psi n c_1 \quad (6)$$

is fulfilled. Here “+” applies to motor operation and “-” to generator operation. n specifies the revolutions per minute.

Commutation

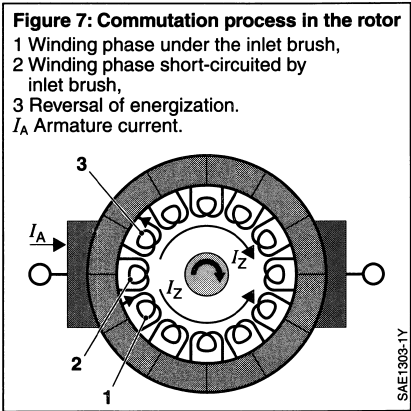
Only the commutator facilitates rotation of the armature and serves to reverse the direction of the current in a winding phase (“commutate” means to change quantities, to transpose with each other, to change the direction of electric current). Commutation is therefore the reversal of the current direction.



The undisturbed stator field distribution is shown in Figure 6a. The undisturbed armature field distribution is drawn in Figure 6b. The two cases are superposed in Figure 6c. This generates a resulting force which allows the armature to rotate to the left. The current direction is reversed by a commutator in Figure 6d while maintaining the direction of armature rotation.

The rotor from Figure 3a is shown enlarged in Figure 7. The armature current I_A is split in each case into branch-circuit currents I_Z . The branch-circuit currents flows into the winding phases of the north and south poles. Beneath the pole faces the current direction in the winding phases is therefore always the same. The current direction changes in each case only in the winding phase to be commutated. The commutation of a winding phase at the inlet brush is given as an example of a commutation. The coils to be commutated are in the neutral zone (NZ). With an accepted right-hand rotation of the rotor the winding phase runs underneath the inlet brush (Figure 7, position 1). Its present current direction is marked with an arrow. In due course the winding phase is short-circuited by the inlet brush (Figure 7, position 2). In position 3 the energization direction of the branch-circuit current was reversed (commutation), which is marked by an arrow.

The time process of commutation within the commutation period T_C can be seen in Figure 8. The start of commutation is marked with t_{CB} and the end of commu-



tation with t_{CE} . The ideal case is complete commutation following the shape of curve 1. Here the effect of the inductive voltages is canceled out by the commutating pole (see following section). The voltage induced by the commutating field is equal to the reactance voltage. Curve shape 2 is called under-commutation. The coil current I decreases from $+I_Z$ only slowly and reaches the current level $-I_Z$ only shortly before the time t_{CE} . The cause of this is an excessively underdimensioned induced commutating-pole voltage.

The opposite to this is curve shape 3, which describes an over-commutation. This is achieved by an excessively high induced commutating-pole voltage.

Basically, the abrupt current change loads the contact system consisting of brush and segment.

The designations have been taken from DIN 1304, Part 7 [7].

Commutating and compensation winding

Compensated machine

Figure 9 depicts a machine provided with a commutating and compensation winding for higher power output (approximately $> 5 \text{ kW}$).

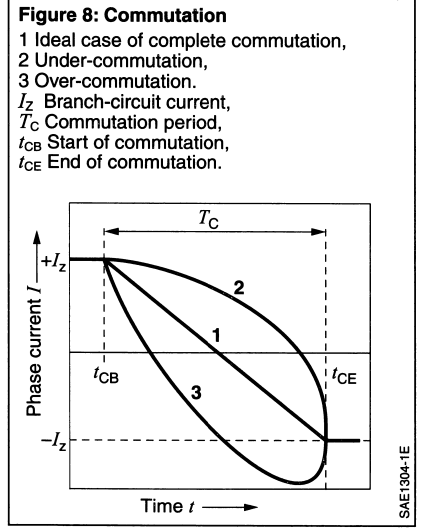
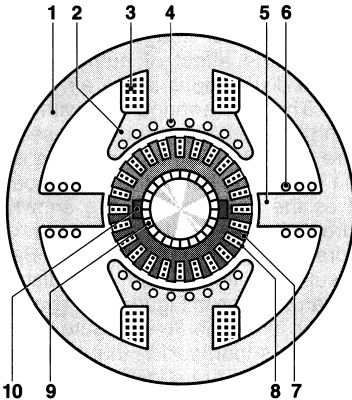


Figure 9: Structure of the two-pole DC machine (cross-section)

- 1 Stator, 2 Exciter pole (pole shoe),
- 3 Exciter winding,
- 4 Compensation winding (preferably on machines with higher power output),
- 5 Commutating pole,
- 6 Commutating winding, 7 Rotor,
- 8 Rotor winding, 9 Commutator lamina,
- 10 Commutator brush (position in the neutral zone).

**Field distribution**

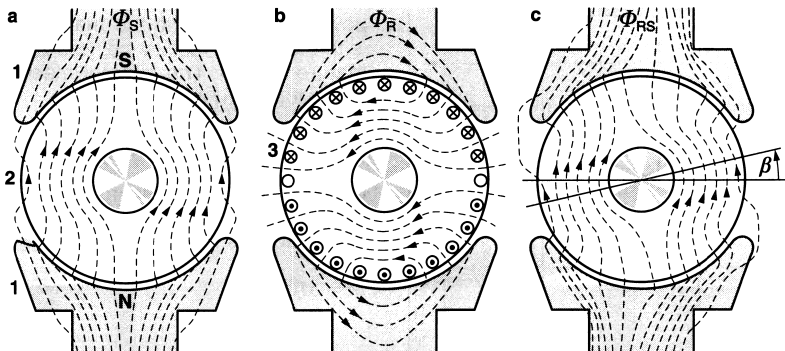
The main field that penetrates the rotor without hindrance when no current is present has a symmetrical distribution (Figure 10a). Likewise, there is a symmetrical flux division when current is applied to only the rotor (Figure 10b). If both fields are superpositioned, the neutral zone is deflected by the angle β (Figure 10c). This magnetically neutral zone thus no longer corresponds to the geometrically neutral zone (position of the commutator brushes). In the geometrically neutral zone, this creates a magnetic field through which a voltage is induced during the commutation process in the coil to be commutated, creating brush sparking (break sparks) between the brush and the running commutator lamina. To prevent this, another voltage is induced during commutation in the coil concerned where the amplitude and direction cancel out the effect of the originally induced voltage.

This is achieved by means of the commutating winding (Figure 9). The commutating winding is connected in series to the rotor winding. It uses rotor retroaction to counteract a shift in the magnetically neutral zone. In the case of motors with-

Figure 10: Superposition of fields

- a) Main field: exciting current switched on, rotor current switched off,
- b) Armature quadrature-axis field: exciting current switched off, rotor current switched on,
- c) Complete field: superposition of main and armature quadrature-axis field;

magnetic neutral zone is deflected by angle β .
 1 Exciter pole (stator pole, main), 2 Rotor, 3 Rotor winding.
 Φ_S Magnetic stator flux (magnetic yoke via the motor housing),
 Φ_R Magnetic rotor flux (magnetic yoke via the exciter pole or motor housing),
 Φ_{RS} Magnetic flux of the complete field.



out commutating windings, the brushes have to be shifted into the magnetically neutral zone.

The main field distortion that occurs in the area of the pole shoe leads to a re-

duction in the available pole surface, combined with an increase in the magnetic resistance. This is why larger machines are given a compensation winding that is integrated in the pole shoes (Figure 9). The compensation winding is connected in series with the rotor winding and its dimensions are such that it compensates for the rotor quadrature-axis field.

Effect of the commutating and compensation winding

The sequence of images in Figure 11 describes the effect of both windings. The field distributions in the air gap are shown. The pole arrangement with winding and the neutral zone can be seen in Figure 11a. The distribution of the excitation field $B_E(x)$ below the pole shoe as well as the pole pitch τ_p are shown in Figure 11b. Figure 11c shows the rotor quadrature-axis field distribution $B_R(x)$. The superposition of both field distributions can be seen in Figure 11d. The compensation induction $B_K(x)$ (Figure 11e) as well as the superposition that took place with Figure 11d are shown in Figure 11f. If the commutating induction $B_W(x)$ in Figure 11g is superposed with the field distribution of Figure 11f, this results in the desired field distribution according to Figure 11h.

Torque and power

The power input (+) or output (-) by the motor at the terminal is

$$P_{el} = P_{th} \pm P_{em} = I_A^2 R_A \pm U_L I_A, \quad (7)$$

where P_{em} corresponds to the internal power and P_{th} to the thermal power, R_A is the armature resistance, and I_A the armature current. The internal mechanical motor torque M corresponds to

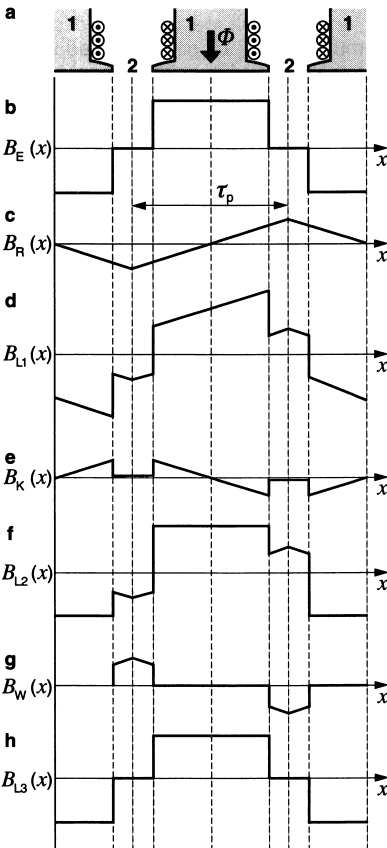
$$M = \frac{P_{em}}{\omega} = \frac{c_1 \Psi n I_A}{2 \pi f} = \frac{c_1}{2 \pi 60} \Psi I_A. \quad (8)$$

For operation at constant rotational speed and mechanical load torque M_{mech} the following applies

$$M = M_{mech}.$$

Figure 11: Effect of the compensation and commutating winding

- Pole arrangement,
 - Distribution of the excitation field $B_E(x)$,
 - Distribution of the rotor quadrature-axis field $B_R(x)$,
 - Superposition of $B_E(x)$ and $B_R(x)$,
 - Compensation induction $B_K(x)$,
 - Superposition of $B_E(x)$, $B_R(x)$ and $B_K(x)$,
 - Commutating induction $B_W(x)$,
 - Superposition of all field distributions.
- 1 Pole shoe, 2 Neutral zone.
 Φ Stator flux.



Shunt-wound machine

A feature of the shunt-wound machine is that the rotor winding is connected parallel to the exciter winding. The following terminal markings (Figure 12) as set out in DIN EN 60034-8 [5] apply to the shunt-wound machine:

- A indicates the armature winding,
- B the commutating winding,
- C the compensation winding, and
- E the shunt field winding.

By transposing equation (6) in accordance with the rotational speed n the speed/current equation follows

$$n(I_A) = -\frac{R_A}{c_1 \Psi} I_A + \frac{U_{Kl}}{c_1 \Psi} \quad (9)$$

as a line equation with a negative slope and axis intercepts

$$n_0(I_A=0) = \frac{U_{Kl}}{c_1 \Psi}; I_{An}(n=0) = \frac{U_{Kl}}{R_A} \quad (10)$$

Here n_0 is the idle speed and I_{An} the starting current. Through the conversion of equation (8) in accordance with the current and insertion in equation (9) the speed/torque equation follows as a line equation

$$n(M) = -\frac{R_A c_2}{c_1^2 \Psi^2} M + \frac{U_{Kl}}{c_1 \Psi}, c_2 = 2\pi \cdot 60 \quad (11)$$

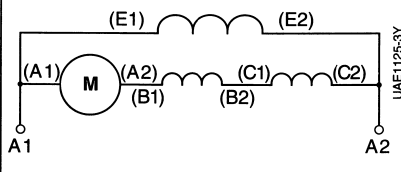
The axis intercepts are given with

$$M(n=n_0) = 0, M_{An}(n=0) = \frac{U_{Kl}}{R_A} \frac{c_1}{c_2} \Psi \quad (12)$$

In Figure 13 the speed is shown against the armature current and the motor torque with four quadrants. Here, motor operation differs from generator operation in each

Figure 12: Terminal markings of the shunt-wound machine

A Rotor winding, B Commutating winding, C Compensation winding, E Exciter winding, M Motor.



case through the direction of rotation and torque. The speed points of the machine can follow by changing the terminal voltage U_{Kl} according to equation (9), which brings about a parallel shift of the straight line in Figure 13. A change of the excitation current separate from the armature current permits according to equation (9) a change of the flux Ψ and thus also a speed change. This measure is called field weakening.

The straight-line slope of equation (9) is changed by a series connection of armature resistance R_A with a series resistance R_V in the armature circuit (Figure 14a). Speed curves with the series resistance as the parameter can be seen in Figure 14b.

Figure 13: Four-quadrant operation of the shunt-wound machine

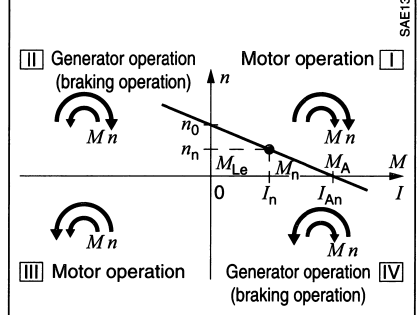
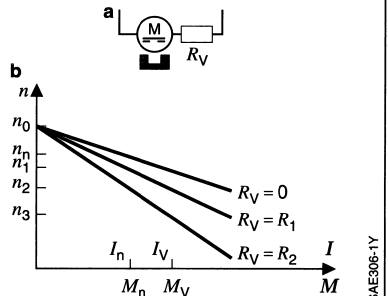


Figure 14: Speed points by means of armature series resistance

- a) Series connection of armature resistance and series resistance,
- b) Speed curves with the series resistance as parameter.



Series-wound machine

In the case of the series-wound machine, the commutating, compensation, exciter, and rotor winding are connected in series (Figure 15). D designates the exciter winding of the series-wound machine. To determine the operating characteristics, the ohmic resistances of the windings are added up to form the resistance R_A . The relationship $\Psi = LI$ and equation (8) inserted in equation (9), the speed/torque equation follows the series-wound machine:

$$n(M) = \frac{1}{c_1 L} \left(U_{K1} \sqrt{\frac{c_1 L}{c_2 M}} - R_A \right). \quad (13)$$

Because of the torque in the denominator the motor achieves reaches high speeds at low load and may never be operated completely without base load. Owing to the absence of external excitation the series-wound commutator machine can only function as a motor. The speed/torque characteristics limits the use of the motor. Areas of application must therefore always provide for a base load (friction torque) as in a vacuum cleaner or in pumps. A small load change always brings about a large speed change. The speed-setting options of the series-wound machine are limited to changing the terminal voltage.

Figure 16 shows the speed/torque diagram of the series-wound machine with the terminal voltage U_{K1} as the parameter.

Asynchronous machine

The asynchronous machine is the main drive used in industry. In the automotive sector, for example, it is used in electrical power-assisted steering and in hybrid vehicles. The following section presents the operating concept of the asynchronous machine as an induction machine.

General setup

A distinction is made between external rotor and internal rotor machines. In the case of the external rotor machine, the rotor encloses the stator; on the internal rotor machine, the stator encloses the rotor.

The diagram of the principle (Figure 17) indicates the fundamental structure of an internal rotor asynchronous machine. The rotor consists in the simplest case of a short-circuited coil (short-circuit rotor). The stator consists of three coils with an iron core which are each assigned to a phase. The iron core consists of individual steel sheets insulated against one another to keep the eddy-current losses to a minimum. The rotating stator magnetic field induces in the short-circuited coil a current which for its part causes a magnetic field which is coupled to the rotating stator field and thus becomes effective in terms of torque.

Figure 15: Terminal markings of the series-wound machine

A Rotor winding, B Commutating winding, C Compensation winding, D Exciter winding, M Motor.

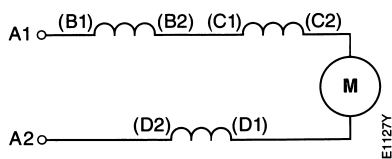
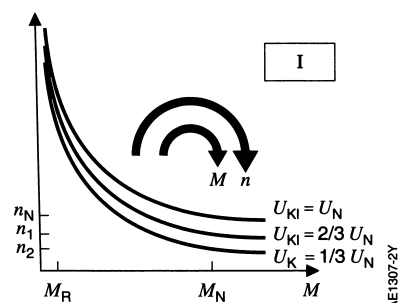


Figure 16: Operation characteristic curves of the series-wound machine

n Motor speed, n_n Rated speed,
 U_{K1} Terminal voltage, U_N Rated voltage,
 M_M Motor torque, M_R friction torque,
 M_N Rated torque.



Operating characteristics

The stator winding generates a rotating field with a three-phase alternating current. There is a speed difference between the rotating-field speed and the rotor speed that enables the induction of a magnetically effective current in the rotor, which in turn contributes to the generation of torque. The physical operating concept is based on the law of magnetic induction. Figure 18 shows the rotor as a simplified conductor loop on rotating mounts. The relative movement between the rotating stator field and the rotor is described by the slip angular frequency ω_s .

The magnetic field B_R rotating with the slip angular frequency induces according to Faraday's law in the cage rotor the voltage

$$\oint E ds = - \int \frac{dB}{dt} dA_s. \quad (14)$$

E denotes the electric field strength along the short-circuit rods and bridges. There follows the development of the left term

- with material ($E = J/\kappa$),
- geometric ($\oint E ds = E \cdot 2(l+2r)$), and
- electrical ($J = i_{\text{ind}}/A_{\text{nom}}$) quantities

$$\oint E ds = \frac{2(l+2r)}{\kappa A_{\text{nom}}} i_{\text{ind}} = R_S i_{\text{ind}}, \quad (15)$$

followed by the development of the right term using geometric ($A_s = 2lr$) and magnetic quantities in the frequency range

$$\int \frac{dB}{dt} dA_s = 2lr \hat{B}_R \omega_s \sin(\omega_s t) = \hat{u}_{\text{ind}} \sin(\omega_s t). \quad (16)$$

Here, κ is the specific electric conductivity, J the current density, and R_S the conductor-loop resistance (short-circuit rods and bridges). By bringing together equations (15) and (16) and converting according to the current i_{ind} there follows

$$i_{\text{ind}} = \frac{\hat{u}_{\text{ind}}}{R_S} \sin(\omega_s t). \quad (17)$$

With the conductor current the tangential force F_t (Lorentz force)

$$F_t = i_{\text{ind}} l \hat{B}_R \sin(\omega_s t) \quad (18)$$

is obtained at the conductor loop. Together with the two rotor rods the torque M follows

$$M = 2F_t r = \frac{2\kappa A_{\text{nom}} \omega_s}{l+2r} (lr \hat{B}_R \sin(\omega_s t))^2 \quad (19)$$

with material, geometric, and magnetic quantities. Including the trigonometric function

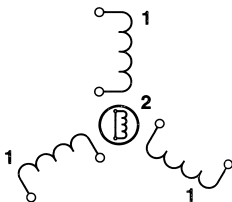
$$\sin^2(\omega_s t) = \frac{1}{2} (1 - \cos(2\omega_s t))$$

the torque M follows again

$$M = \frac{\kappa A_{\text{nom}} \omega_s}{l+2r} (lr \hat{B}_R)^2 (1 - \cos(2\omega_s t)). \quad (20)$$

Figure 17: Principle of a three-phase asynchronous motor

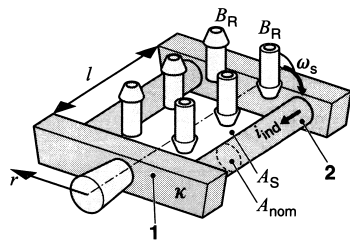
- 1 Fixed stator winding,
- 2 Rotor as rotatable short-circuited coil. Axis of rotation perpendicular to the plane of projection.



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Figure 18: Two-bar rotor as short-circuit rotor

- 1 Short-circuit bridge, 2 Short-circuit rod.
- i_{ind} Induced current, l Short-circuit rod length,
- r Rotor radius, A_{nom} Rod cross-sectional area,
- B_R Magnetic field rotating with slip angular frequency,
- A_s Cross-sectional area of conductor loop,
- κ Specific electric conductivity of conductor loop,
- ω_s Slip angular frequency (results from the relative movement between stator rotating field and rotor speed).



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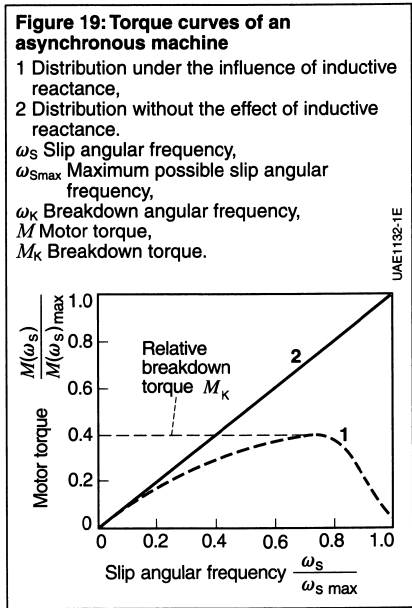
This is made up of a constant and a time-variable component of oscillating torque at twice the slip angular frequency. The amplitude of the oscillating torque corresponds to the amount of the constant component. The magnetic effect of the induced current in the conductor loop is taken into account as follows. The current causes, on account of Ampère's law, the induced magnetic field H_{ind} and the field strength the induced magnetic flux density B_{ind} :

$$H_{\text{ind}} = \frac{i_{\text{ind}} N}{l_H}, \quad B_{\text{ind}} = \mu H_{\text{ind}}. \quad (21)$$

Here, N is the number of conductors and l_H the field-line length. The power loss P_V obtained in the rotor is calculated at

$$P_V = R_S i_{\text{ind}}^2 = \frac{l_S}{\kappa A_{\text{nom}}} i_{\text{ind}}^2 \quad (22)$$

Figure 19 shows torque curves as a function of the slip angular frequency.



Synchronous machine

Synchronous machines are used preferably as claw pole generators. In motor operation, they are used for example in electrical power-assisted steering, to drive hybrid vehicles, and in electrically driven turbochargers.

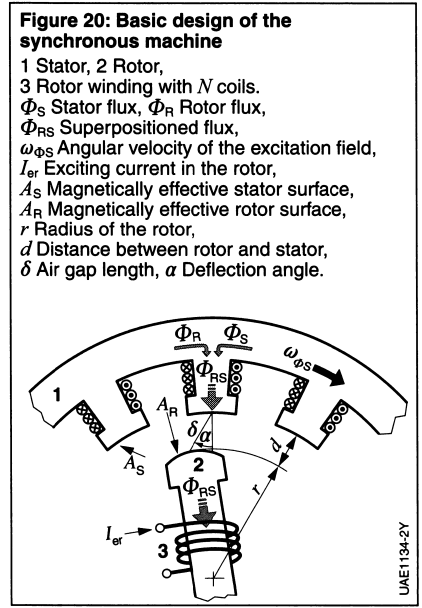
General setup

In contrast to the asynchronous machine, in the synchronous machine the rotor rotates synchronously with the excitation field at the angular velocity $\omega_{\Phi S}$. The flux Φ_R generated by the rotor winding and the stator flux Φ_S superposition themselves in relation to the resulting flux Φ_{RS} (Figure 20):

$$\Phi_{RS} = \Phi_R + \Phi_S. \quad (23)$$

As the rotor and stator material are operated far below the magnetic saturation ($\mu_r \rightarrow \infty$), the air gap d between the rotor and stator as well as the angle α determine the magnetic circuit resistance R_m :

$$R_m = \frac{2\delta}{(\mu_0 A_R)} = \frac{2d}{(\mu_0 A_R \cos \alpha)}. \quad (24)$$



The factor 2 results from the fact that there are two air gaps between the rotor and stator. If the motor provides torque, the rotor rotates with the angle α from its idle position (Figure 21).

The resulting flux Φ_{RS} is calculated as:

$$\Phi_{RS} = \frac{\Theta_{er}}{R_m} + \Phi_S. \quad (25)$$

With R_m from equation (24), this results in

$$\Phi_{RS} = \frac{\Theta_{er}\mu_0 A_R \cos \alpha + 2d\Phi_S}{2d}. \quad (26)$$

With $\Theta_{er} = NI_{er}$ the result is

$$\Phi_{RS} = \frac{NI_{er}\mu_0 A_R \cos \alpha + 2d\Phi_S}{2d}. \quad (27)$$

Θ_{er} is the magnetic rotor flooding and I_{er} is the exciting current fed to the rotor via the collector rings. The tangential force F_t affecting the torque is calculated using the Maxwell pole force formula

$$F_t = \frac{\Phi_{RS}^2}{\mu_0 A_R} \sin \alpha \quad (28)$$

[4, 5, 8]. The tangential force is used to calculate the motor torque M_M :

$$M_M = 2F_t r. \quad (29)$$

Equation (27) inserted in equation (28) and the result in equation (29) yields the following relationship:

$$M_M = \frac{r \sin \alpha}{2\mu_0 A_R d^2} \cdot [(NI_{er}\mu_0 A_R \cos \alpha)^2 + 4NI_{er}\mu_0 A_R d\Phi_S \cos \alpha + 4d^2\Phi_S^2]. \quad (30)$$

The first term is only dependent on the exciting current I_{er} and corresponds to the cogging torque. The second term generates the motor torque to a decisive degree. The linear dependency of the rotor flooding $\Theta = I_{er}N$ and stator flux Φ_S can be seen here. The third term also generates a torque and is only dependent on the stator flux [8]. Operation of the motor with only the third term corresponds to operation of a reluctance motor.

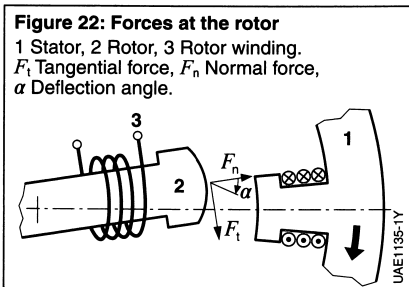
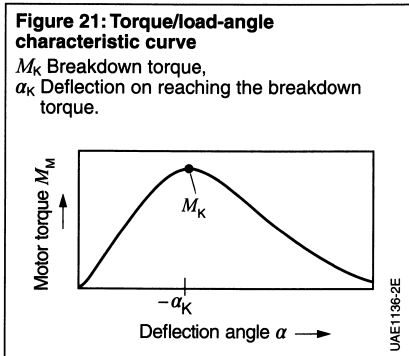
An increase in the outer load torque leads to an increase in the load angle α and thus to a change in motor torque M_M to be delivered (Figure 22). The maximum motor torque to be delivered is referred to as the breakdown torque M_k at the position α_k . If α_k is exceeded, the machine slips out.

Alternatively, the torque can also be calculated approximately via the Lorentz force F_L [9]. This is the force which acts on moving charges in a magnetic field and is defined as

$$\vec{F}_L = I (\vec{l} \times \vec{B}) \quad (31)$$

Here, I is the current in the conductor, l the length of the conductor, and B the flux density of the effective magnetic field. Vectorial notation and the cross product mean that conductor and magnetic field must be perpendicular to each other in order to fashion a force.

By introducing an electric loading A which fashions the currents in the individual conductors of a machine at a fictitious line current density along the periphery, the Lorentz force



$$\vec{F}_L = A (\vec{S} \times \vec{B}) \quad (32)$$

can be described with the aid of the air-gap area S between the rotor and the stator. For the effective value of the electric loading the following applies

$$A = \frac{\hat{A}}{\sqrt{2}} \quad (33)$$

with sinusoidal flux distribution. The peak value of the electric loading is expressed with the number of stator phases m , the number of turns per phase N , and the pole pitch τ_p at the middle air-gap radius r_δ as

$$\hat{A} = \frac{m\sqrt{2}NI}{p\tau_p} = \frac{m\sqrt{2}NI}{\pi r_\delta}. \quad (34)$$

With the rotor length l in the axial direction the air-gap area S is obtained

$$S = 2\pi r_\delta l. \quad (35)$$

The mean value of a pole pitch is used for the flux density B . If the flux-density distribution along the periphery has a sinusoidal characteristics with the amplitude $\hat{B}$, then its mean value is given as

$$\begin{aligned} B &= \frac{1}{\pi} \int_0^\pi \hat{B} \sin(p\alpha) d\alpha \\ &= \frac{2}{\pi} \hat{B} \\ &\approx 0.64 \hat{B}. \end{aligned} \quad (36)$$

With the relationship $M = r_\delta F_L$ the torque

$$M_M = 2mNIBlr_\delta \quad (37)$$

follows for a stationary operating state.

Suppression of harmonics

A sinusoidal flux distribution along the periphery of a stator is technically not feasible, therefore harmonics occur during operation in addition to the principal wave of the magnetic field. These lead to unwanted fluctuations of torque, vibrations, and additional losses. In order to specifically suppress the influence of certain magnetic-field harmonics, the rotor or stator slots are often skewed in electric machines. The skewing is intended to ensure that the same face of north and south poles of the harmonic to be neutralized are enclosed by the turns of a coil. The magnetic fluxes of these poles thus counterbalance each other and no longer impact negatively on the machine's operating characteristics.

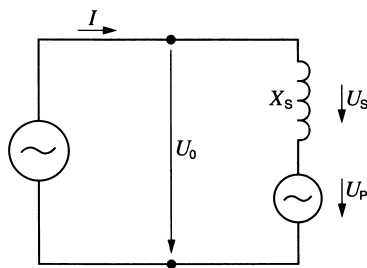
Another way of suppressing harmonics comes from the spatial distribution and chording of the coils. The effect of spatial distribution and chording is reflected in the winding factor. This is a measure of the coupling of windings with the respective magnetic flux-density waves.

Operating characteristics

A drawing of the synchronous machine can be made in a single-phase equivalent electric circuit diagram in that the voltage induced by the rotor in the stator (pole-wheel voltage U_p) is assumed as the voltage source and remaining reactances (inductive resistances) are summarized

Figure 23: Single-phase equivalent circuit diagram of the synchronous machine

U_p Pole-wheel voltage,
 U_s Reactance voltage,
 U_0 Terminal voltage,
 I Current,
 X_s Synchronous reactance.



to form the synchronous reactance X_S (Figure 23). The voltage above the synchronous reactance is designated U_S and the terminal voltage U_0 . The direction of the current is specified in accordance with the consumer unit counting arrow system. Whereas current flows into the consumer units during motor operation, current flows out of the generator during generator operation. Setting up the mesh equation yields the current I

$$I = \frac{U_0 - U_P}{X_S} \quad (38)$$

The amount of the pole-wheel voltage is influenced by the exciting current. The relationships are to be derived below. The following applies:

$$U_P = -\frac{d\Phi_R}{dt} \quad (39)$$

With the cosinoidal flux Φ_R and the relationship

$$\Phi_R = B A_S \quad (40)$$

including its temporal derivation, this leads to

$$\begin{aligned} u_P &= \Phi_R \omega_{\Phi S} \sin(\omega_{\Phi S} t) \\ &= B_R A_S \omega_{\Phi S} \sin(\omega_{\Phi S} t) \\ &= \mu H_R A_S \omega_{\Phi S} \sin(\omega_{\Phi S} t). \end{aligned} \quad (41)$$

The magnetic field intensity created in the rotor is described by Ampère's law. The pole-wheel voltage

$$\begin{aligned} u_P &= \mu \frac{\Theta_R}{2\delta} A_S \omega_{\Phi S} \sin(\omega_{\Phi S} t) \\ &= I_{er} \frac{\mu N}{2\delta} A_S \omega_{\Phi S} \sin(\omega_{\Phi S} t) \\ &= \hat{u}_P \sin(\omega_{\Phi S} t) \end{aligned} \quad (42)$$

is then linear-dependent on the exciting current I_{er} . The temporally changeable pole-wheel voltage is converted into its effective value using

$$U_P = \frac{\hat{u}_P}{\sqrt{2}} \quad (43)$$

On the basis of the mesh equation (38), three operating states of the synchronous machine can be derived depending on the pole-wheel voltage (Figure 24):

- Case 1: $U_P < U_0$, underexcitation, inductive,
Case 2: $U_P = U_0$, resistive,
Case 3: $U_P > U_0$, overexcitation, capacitive.

The first case occurs as long as $U_P < U_0$. If $I_{er} = 0$, only the self-induction voltage is effective as induced voltage. If current is applied to the rotor, the mutual induction caused by the rotor also takes effect. The first case is referred to as underexcitation. The current lags behind the voltage by 90° ($\varphi(I, U) < 0$). The synchronous machine shows inductive characteristics.

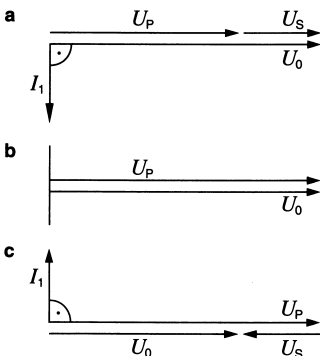
Another increase in the exciting current leads to $U_P = U_0$. This produces the second operating case (Figure 24b). The current I_1 becomes zero if no more voltage is supplied via the synchronous reactance.

Another increase in the rotor current leads with $U_P > U_0$ to the third operating case (overexcitation).

All three cases apply to motor and generator operation. For the single-phase equivalent circuit diagram, the pointers are applied to the voltages and currents. Furthermore, the load angle β that sets

Figure 24: Operating states of the synchronous machine at idle

- a) Underexcitation (inductive),
b) $I = 0$ (resistive),
c) Overexcitation (capacitive).
 U_P Pole-wheel voltage,
 U_S Reactance voltage,
 U_0 Terminal voltage, I_1 Stator current.



in between the voltages U_0 and U_S is defined. For motor operation, the load angle β is < 0 (Figure 25a). The voltage triangle is closed by the voltage U_S .

The synchronous reactance means that the current I_1 leading by 90° in relation to the voltage U_S flows. This is broken down into its components: the active current I_W and reactive current I_B (Figure 25a).

If the pole-wheel voltage is reduced so that the pointer of the reactance voltage is vertically on the pointer of the terminal voltage U_0 , the motor only consumes active current (Figure 25b).

A further reduction in the pole-wheel voltage leads to underexcitation. The current I_1 lags behind the voltage U_S by 90° , which is the equivalent of inductive characteristics of the motor (Figure 25c). If torque is applied to the motor, it switches to generator operation. Generator operation features the positive load angle β

(Figure 26). The sign of the current becomes negative. Current flows out of the machine. In the case of overexcitation, the machine behaves like a capacitor. It delivers reactive power (Figure 26a).

If the pole-wheel voltage is reduced so that the pointer of the reactance voltage U_S is vertically on the pointer of the terminal voltage, the generator only delivers active current (Figure 26b).

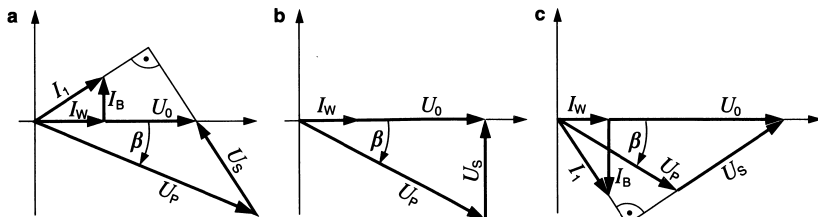
A further reduction in the pole-wheel voltage leads to a case of underexcitation. The machine behaves inductively. It consumes reactive power (Figure 26c).

Figure 25: Operating characteristics of the synchronous machine in motor operation

a) Overexcitation, b) Motor operation with consumption of active current, c) Underexcitation.

U_0 Terminal voltage, U_S Reactance voltage, U_P Pole-wheel voltage,

I_1 Current, I_W Active current, I_B Reactive current, β Load angle.



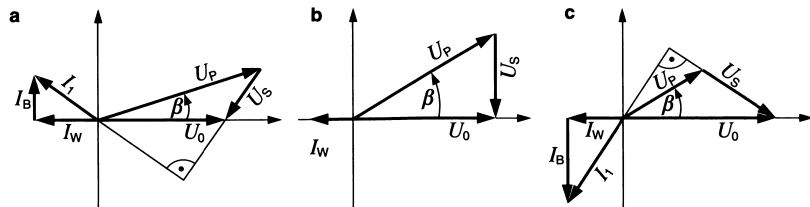
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Figure 26: Operating characteristics of the synchronous machine in generator operation

a) Overexcitation (capacitive), b) Operation with active current delivery, c) Underexcitation (inductive).

U_0 Terminal voltage, U_S Reactance voltage, U_P Pole-wheel voltage,

I_1 Current, I_W Active current, I_B Reactive current, β Load angle.



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Starting synchronous motors

Synchronous motors then only generate a permanently positive torque when the rotor and rotating-field speeds match. If this is not the case, the rotor's magnet poles are alternately attracted and repelled. The rotor starts to oscillate and also heats up strongly since the current consumption is not limited by the induced pole-wheel voltage. In the worst case the insulation of the windings is destroyed by the thermal load. To stop this from happening, the machine rotor must first be accelerated to synchronous speed. Three procedures have proven successful in the past for this purpose.

Procedure 1

The rotor is accelerated with the aid of a DC motor to synchronous speed before being put into operation.

Procedure 2

In salient-pole rotors a cage winding, also called a damper winding, can be integrated in the pole shoe. A structure of this type is pictured in Figure 27. This winding delivers in asynchronous mode the necessary torque to accelerate to synchronous speed. The windings are additionally short-circuited and deliver a further small torque contribution during running-up. If the machine is already at rotational speed, no further currents are induced on account of the absence of relative speed between rotor and stator speeds.

Procedure 3

The rotating-field speed is adapted with frequency converters to the rotor speed and slowly increased up to synchronous speed.

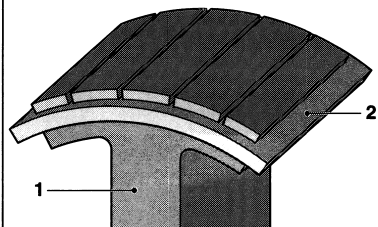
Switched reluctance motor**Properties of the switched reluctance motor**

The "switched reluctance motor" (SRM) belongs to the class of synchronous motors. Its mode of operation is based on the effect of force on a boundary layer (reluctance force). Its design is comparable with many parallel-switched magnetic circuits which are continuously cyclically energized. Cyclic energization (switching with the necessary ECU) of stator-magnet teeth makes possible a rotary motion whereby the rotor teeth are brought into line with the stator teeth. Since rare-earth materials do not have to be used, areas of application open up in which motors with permanent-magnet material cannot be used. Areas of application at high temperatures are mentioned here by way of example.

The switched reluctance motor is suitable for variable-speed drive tasks and for positioning tasks. Thanks to its design, it can generate a holding torque over an extended period of time. It also generates high torque fluctuations.

Figure 27: Salient pole with integrated cage winding

- 1 Salient pole,
- 2 Cage winding.



Design of the switched reluctance motor

Figure 28 shows a cross-section of a four-phase ($m = 4$) switched reluctance motor. In the snapshot of Figure 28 the stator windings are energized (marked in dark gray in the figure). The current drives a magnetic flux through the four-pole arrangement of teeth A1, A2, A3, and A4. Since the rotor and stator teeth do not line up, a reluctance force is generated at the rotor-tooth surfaces whose tangential component has a torque-producing effect and can thus turn the rotor clockwise. The torque becomes zero as soon as the rotor and stator teeth line up. It is necessary to switch to further windings at the latest at the onset of this condition (see also [7], [10], [13]).

Calculating the number of stator and rotor teeth

A magnetic circuit provided with a phase winding contains a ferromagnetic flux concentrator (yoke and armature) and always an air gap for energy conversion. Two series-connected air gaps are required in the same magnetic circuit to facilitate a rotation of the armature. The magnetic

flux penetrates the air gap once from the rotor to the stator and back from the stator to the rotor to complete the circuit. This is combined in a pole pair of the reluctance motor $Z_p = 1$. This also means that in this example $2Z_p$ is equal to the number of pole pairs per phase. The number of stator teeth N_s will be inferred by means of consideration whereby two rotor/stator teeth pairs in line (rotor tooth facing stator tooth) per phase form a magnetic circuit with the lowest reluctance (greatest inductance). Multiplying the number of poles per phase by the number of phases m produces the number of stator teeth $N_s = 2mZ_p$. To obtain a relative movement of the rotor in relation to the stator, it is necessary to achieve asymmetry of the numbers of teeth of stator and rotor. A practicable formulation for calculating the number of rotor teeth N_R is

$$N_R = N_s \pm \Delta N$$

$$= m \cdot 2 Z_p \pm 1 \cdot 2 Z_p$$

$$= 2 Z_p (m \pm 1). \quad (44)$$

The number of rotor teeth differs here precisely by an in-line tooth pair (pole pair) of a single phase (difference ΔN). Because of the magnetic flux between rotor and stator teeth, $N_R = 2Z_p(m + 1)$ is preferred for an external rotor and $N_R = 2Z_p(m - 1)$ is preferred for an internal rotor. For example, in Figure 28

$N_s = 2Z_p m = 2 \cdot 2 \cdot 4 = 16$ stator teeth and $N_R = 2Z_p(m - 1) = 2 \cdot 2 \cdot (4 - 1) = 12$ rotor teeth can be seen.

Calculating the step angles

Calculation of the step angle applies to the controlled stepping motor. The difference between stator angle α_s and rotor angle α_R where

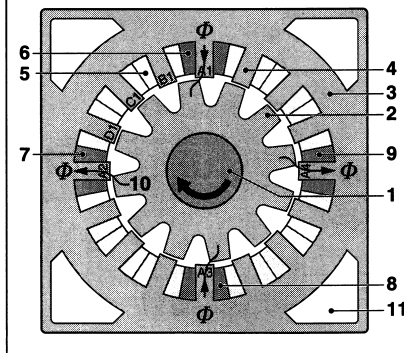
$$\alpha_s = \frac{2\pi}{N_s} = \frac{2\pi}{m \cdot 2Z_p} \quad \text{and}$$

$$\alpha_R = \frac{2\pi}{N_R} = \frac{2\pi}{2Z_p(m \pm 1)} \quad (45)$$

Figure 28: Design of a switched reluctance motor as internal rotor

- 1 Rotor shaft, 2 Rotor tooth,
- 3 Stator, 4 Stator teeth,
- 5 Non-energized stator winding,
- 6, 7, 8, 9 Energized stator windings,
- 10 Flux Φ ,
- 11 Cooling channel.

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yields the step angle θ where

$$\begin{aligned}\theta &= \alpha_S - \alpha_R \\ &= \frac{2\pi}{m \cdot 2Z_p} - \frac{2\pi}{2Z_p(m \pm 1)} \\ &= \frac{\pm \pi}{Z_p m(m \pm 1)} \\ \theta &= \frac{-\pi}{Z_p m(m-1)} = \frac{-\pi}{2 \cdot 4(4-1)} = -\frac{\pi}{24}.\end{aligned}\quad (46)$$

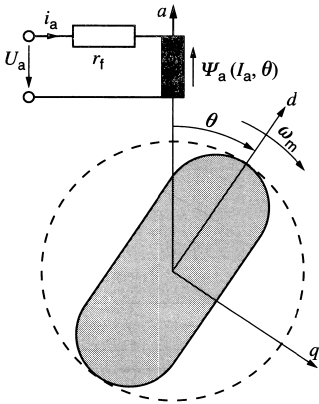
Changing the step angle θ after the time t produces the angular velocity ω_m , from which the rotational frequency f_r is calculated. For example, for the stepping motor from Figure 28 a step angle $\theta = -\pi/24$ (see equation (46)) with a rotational frequency f_r is obtained:

$$f_r = \frac{1}{2\pi} \frac{d\theta}{dt}.\quad (47)$$

The rotor runs opposite to the phase switching direction.

Figure 29: Schematic representation of the switched reluctance motor

d Direct axis, q Quadrature axis,
 a Strand (phase),
 ω_m Rotor angular velocity,
 θ Step angle,
 Ψ_a Flux linkage of stator winding,
 U_a Phase voltage, I_a Phase current,
 r_l DC resistance of excitation winding.



Single-phase equivalent circuit diagram of the switched reluctance motor

The equivalent circuit diagram of the switched reluctance motor reduced to a phase a is depicted in Figure 29. The symbols and designations have been taken from VDI/VDE 3680 [10].

Operating characteristics of the switched reluctance motor

Voltage relationship

The operating characteristics are presented using the example of the voltage-differential and torque equation. The voltage-differential equation of the nonlinear magnetic circuit

$$\begin{aligned}u_a(t) &= u_R(t) + u_L(t) \\ &= i_a(t)r_l + \frac{d\Psi_a(I_a, \theta)}{dt}\end{aligned}\quad (48)$$

is set up with the aid of Figure 29. By forming the total differential of $\Psi_a(I_a, \theta)$ and inserting in the voltage-differential equation it follows that

$$u_a(t) = i_a(t)r_l + \frac{\partial \Psi_a}{\partial I} \frac{di_a}{dt} + \frac{\partial \Psi_a}{\partial \theta} \frac{d\theta}{dt}.\quad (49)$$

To emphasize the angle dependence of the inductance, there follows with $\Psi_a = L_r(\theta)I_a$ the first-order non-homogeneous voltage-differential equation

$$u_a(t) = L_r(\theta) \frac{di_a}{dt} + \left(r_l + \frac{\partial L_r(\theta)}{\partial \theta} \frac{d\theta}{dt} \right) i_a.\quad (50)$$

It is clear that the induced voltage exhibits a proportionality to the rotor angular velocity. As the angular velocity increases the induced voltage rises, which has a current-lowering and thus torque-reducing effect, as is shown in the following.

Torque relationship

With the aid of the angle-dependent co-energy $W_{\text{mag}}^{\text{Co}}$ of the linear (Figure 30a) and nonlinear magnetic circuits (Figure 30b) the mechanical energy W_{mech} follows where

$$\begin{aligned}\Delta W_{\text{mag}}^{\text{Co}} &= W_{\text{mag}}^{\text{Co}}(\theta_1) - W_{\text{mag}}^{\text{Co}}(\theta_2) \\ &= W_{\text{mech}}.\end{aligned}\quad (51)$$

The magnetic co-energy $W_{\text{mag}}^{\text{Co}}$ corresponds to the area (energy) below the respective characteristic.

The co-energy together with the magnetic energy always produce a rectangle or a square in the diagram. With the restriction to the linear magnetic circuit according to Figure 30a it follows that

$$\Delta W_{\text{mag}}^{\text{Co}} = \frac{1}{2} I_a^2 (L(\theta_1) - L(\theta_1))$$
$$= W_{\text{mech}}.$$

What is clear is the quadratic current function, which decisively influences the area W_{mech} . The larger this area, the greater the rated torque m_A ,

$$m_A = \frac{\partial W_{\text{mech}}}{\partial \theta},$$

which is calculated with the angle-dependent co-energy. In the angle position θ_1 the rotor and stator teeth face each other in line. In this angle position the minimum reluctance and consequently the maximum interlinked flux Ψ_{max} are obtained. The torque equals zero in this position. A torque is obtained in the angle position θ_2 . The stator tooth faces the rotor groove. The reluctance value assumes a maximum, the flux Ψ a minimum.

The symbols and abbreviations used have been taken from VDI/VDE 3680 [10].

Electronic motors

In the case of electronically commutating motors (electronic motor, EC motor), the rotor excitation winding, including the electrical contacting with collector rings, is not required. Electronic motors are brushless synchronous motors where the rotors are fitted with permanent magnets. The permanent magnets can be arranged, for example, on the rotor surface or in the rotor (Figure 31). The commutation of the current takes place generally in the fixed stator winding by means of an electronic assembly (Figure 33).

Figure 31: Variations of rotors for the electronic motor

- a) Rotor with surface magnets,
 - b) Rotor with embedded magnets (buried magnets).
- Φ Rotor flux.

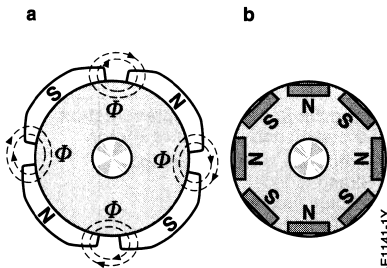
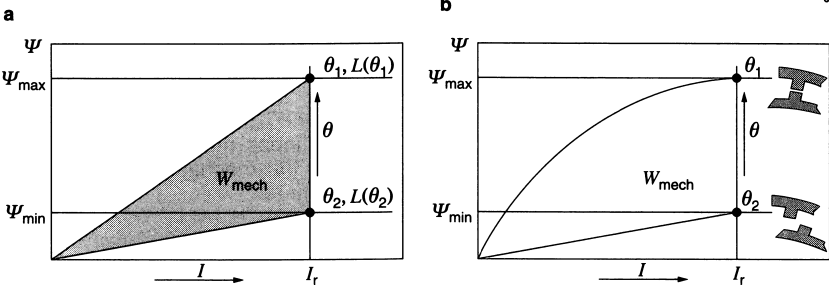
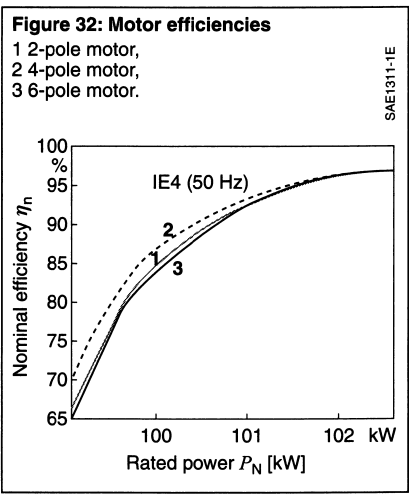


Figure 30: Torque-producing mechanical energy

- a) Linear magnetic circuit,
- b) Nonlinear magnetic circuit.



The rotational speed of the electronic motor is set by the frequency of the surrounding stator field. Sensors are required to pick up the rotor position. Widespread use is made of Hall sensors fitted in the working air gap to enable cyclic relaying between the winding phases with the help of activation electronics.



Energy-efficiency classes

The International Electrotechnical Commission (IEC) intends with the standard IEC 60034 Part 30-1 [8] to harmonize internationally efficiency classes for electric motors. The standard applies to all types of electric motors which are rated for direct start-up at the power system. The efficiency classes are named in Table 3. In Figure 32 the motor efficiencies are plotted against the rated power for 2-, 4- and 6-pole motors at 50 Hz.

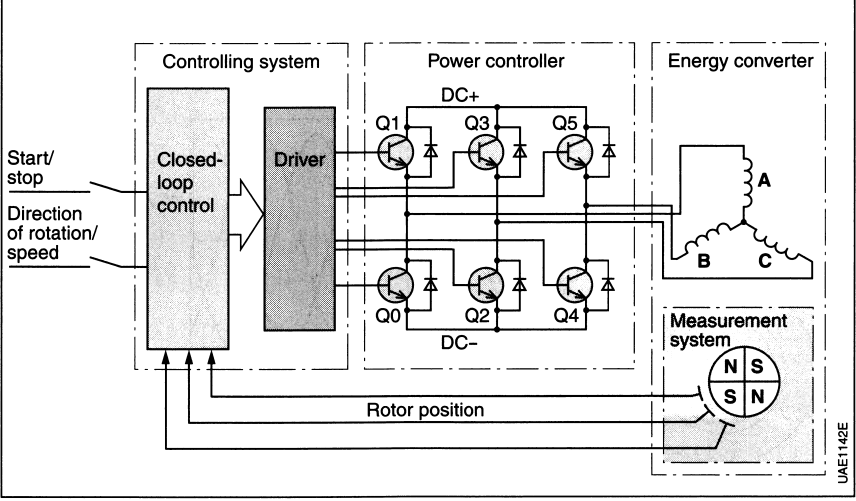
The area of application of the IE4 standard is presented in a shortened version:

- Rated power P_N :
0.12 kW through 1000 kW;
- Rated voltage U_N :
50 V through 1 kV;
- Number of poles from 2, 4, 6 or 8.

Table 3: Efficiency classes

Abbreviation	Name
IE1	Standard-Efficiency
IE2	High-Efficiency
IE3	Premium-Efficiency
IE4	Super-Premium-Efficiency

Figure 33: Activation electronics of the electronic motor



Three-phase current system

Technically relevant is the application of the three-phase alternating current system as a three-phase current system, the major feature of which is that the total of all voltages and currents is zero at all times.

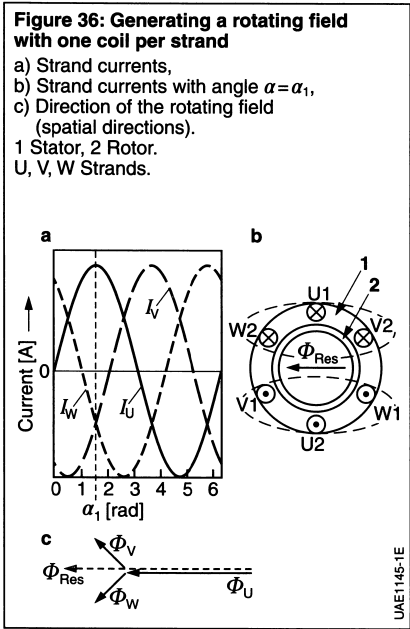
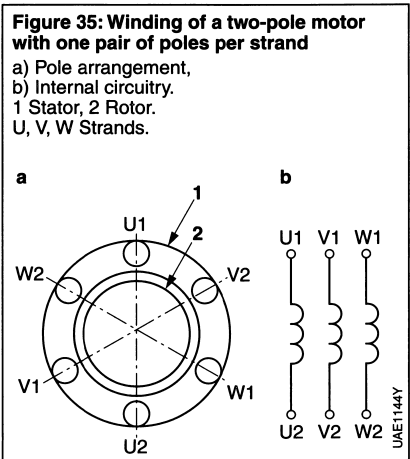
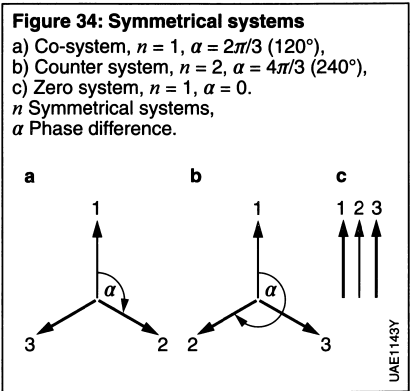
Definitions

The electric circuits are referred to as phases *m*. The total of the electric circuits in which voltages of the same frequency have an effect and are phase-shifted are referred to as multiphase systems. A multiphase system consists of winding phases. On a three-phase system, *n* = 3 symmetrical systems are possible (Figure 34). On all

symmetrical systems – with the exception of the zero system – the total of all point-ers is zero. *m* phases result in *n* different symmetrical systems depending on the phase difference *α*:

$$\alpha = \frac{2\pi n}{m} . \tag{52}$$

The task of windings is to generate a rotating field. Asynchronous and synchronous machines have the same stator structure. In the air gap, a magnetic field with constant amplitude is to be created, rotating at constant angular velocity. For this rotating field to be generated, the temporal phase positions of the currents must match the spatial position of the corresponding strands. For a simple symmetrical system (*n* = 1) with *m* = 3, the three strands (designated with U, V and W) and therefore the windings must be evenly distributed over the circumference. Figure 35 shows the arrangement of a three-strand winding with one coil per pair of poles and strand The terminal markings of the phases comply with DIN EN 60034, Part 8 [8].



Rotating-field generation

In order to generate a rotating field in the case of a simple symmetrical system ($n = 1$) with the number of strands $m = 3$, the strands must be geometrically offset by the electrically effective angle

$$\alpha_{el} = 360^\circ \cdot \frac{1}{3} = 120^\circ.$$

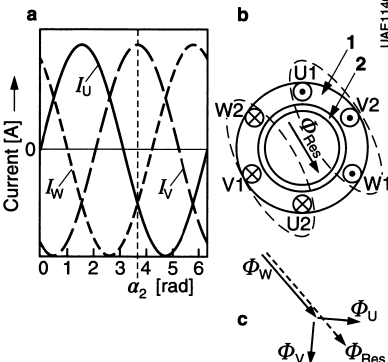
With one coil per pair of poles and strand, the resulting magnetic field rotates counterclockwise in that the “indicator bar” shifting in Figure 36a to the right (at $\alpha = 90^\circ$) indicates the phase current in each of the strands in Figure 36b in flux direction. The arrangement forms a pair of poles. The associated magnetic fluxes emerge vertically in relation to the winding plane of the strands (Figure 36b).

The flux Φ_{Res} (Figure 36c) resulting from the three strands as well as its direction are achieved by geometrically adding up the three individual fluxes Φ_U , Φ_V and Φ_W .

A progression of the indicator bar up to $\alpha = 180^\circ$ leads to a current-direction reversal in strand W and therefore to a further turn to the right of the resulting field Φ_{Res} (Figure 37).

Figure 37: Generating a rotating field with one coil per strand

- a) Strand currents,
b) Strand currents with $\alpha = \alpha_2$,
c) Direction of the rotating field (spatial directions).
1 Stator, 2 Rotor.
U, V, W Strands.



UAE1146-2E

When two coils per strand are used, the conductor arrangement is “doubled”. If the winding is to form two pairs of poles ($p = 2$), the windings have to be divided into groups (Figure 38). With this, the mechanically effective angle

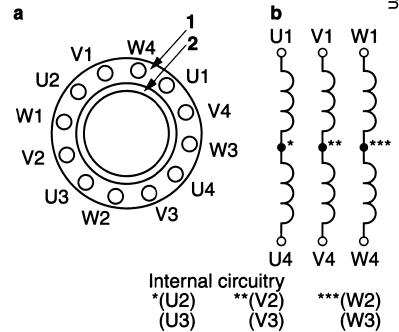
$$\alpha_m = 360^\circ \cdot \frac{1}{m \cdot p} = 60^\circ \text{ sets in.}$$

Figure 38: Winding with two pairs of poles per strand

- a) Pole arrangements,
b) Example of the internal wiring of the four-pole motor with two windings per pole pair and strand.

The interconnections in parentheses are internal and thus inaccessible.

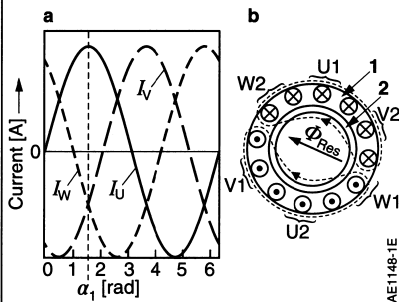
1 Stator, 2 Rotor.
U, V, W Strands.



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Figure 39: Rotating-field generation with two coils per strand

- a) Strand currents with angle $\alpha = \alpha_1$,
b) Resulting magnetic field with $\alpha = \alpha_1$.
1 Stator, 2 Rotor.
U, V, W Strands.



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The electrically effective angle remains unchanged. In the case of both the two-pole and four-pole arrangement, the field rotates counterclockwise (Figure 39). The rotating-field speed

$$n_d = \frac{f_n}{p}$$

can be calculated with the mains frequency f_n and the number of pole pairs p . For $p = 1$, the rotating-field speed is equal to the mains frequency (Table 4).

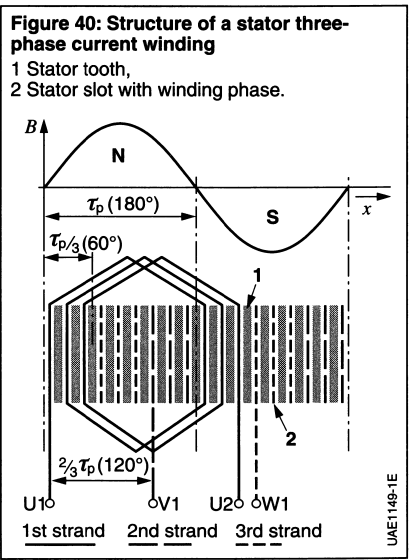
Together with the number of pole pairs, the pole pitch

$$\tau_p = \pi d_{si}/2p$$

can be calculated as a stator circumference proportion, where d_{si} is the inner diameter of the stator. It corresponds to the length of a sinusoidal half wave that corresponds to the induction distribution of the rotor field. In the case of a two-pole machine ($p = 1$), the pole pitch is $\alpha_{el} = 180^\circ$ (electrical angle) at all times and matches

Table 4: Rotating-field speeds

Pair of poles p	n_0 [rpm] at $f = 50$ Hz
1	3000
2	1500
3	1000



the mechanical angle α_m . The relationship of the two angles is indicated by $\alpha_{el} = p \alpha_m$. So that voltages of equal size are induced in the windings, the winding phases have to be offset in relation to one another by $\alpha_{el} = 120^\circ$ or $2\tau_p/3$ and the coil structure and number of turns must be the same. One third of the pole pitch is apportioned to each strand.

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THE HISTORY OF THE UNITED STATES

The history of the United States is a story of growth and development. It begins with the first settlers, who came to the New World in search of a better life. They found a land of opportunity, but also a land of challenge. The early years were marked by conflict and struggle, as the settlers fought to establish their communities and defend their rights. Over time, the United States grew from a small colony into a powerful nation. It expanded its territory, developed its economy, and established a system of government that has inspired the world. The history of the United States is a testament to the power of the American dream and the strength of the American people.

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Alternators

Electric power generation

Motor vehicles need an alternator to charge the battery and to supply the electrical equipment such as ignition and fuel-injection systems, ECUs, lights, etc. with power. To charge the battery, it is necessary for the alternator to generate more current than is required by the electrical equipment when switched on. The alternator output, the battery capacity and the power demand of the electrical equipment must be matched to each other to ensure that under all operating conditions enough current is supplied to the vehicle electrical system and the battery is always sufficiently charged. This results in a consistent charge balance.

Because the battery and many items of electrical equipment have to be supplied with direct current, the alternating current generated by the alternator is rectified. The alternator is equipped with a voltage regulator so that it can supply the battery and the electrical equipment with a constant voltage. Alternators in passenger cars are designed for charge voltages of 14 V and those in many commercial vehicles for 28 V (28 V electrical system).

Requirements

The essential alternator requirements are:

- maintenance of a direct-voltage supply to all electrical equipment in the system,
- charging reserves for (re)charging the battery, even at a constant load from electrical devices in continuous operation,
- maintenance of a constant alternator voltage throughout the entire ranges of engine speed and load conditions,
- high level of efficiency,
- low operating noise,
- robust design capable of withstanding external stresses (such as vibration, high ambient temperatures, temperature cycles, dirt, moisture),
- long service life, comparable with that of the vehicle itself (for passenger cars)
- low weight,
- compact dimensions.

Principle of electromagnetic induction

To generate an alternating current a conductor loop is rotated between the north and south poles of a permanent magnet (Figure 1). If, as a result of the rotation of the conductor loop, the magnetic field in this conductor loop changes, a voltage is induced in it. According to Faraday's law of induction, the induced voltage U_{ind} increases as the speed v of the motion vertical to the field lines increases and as the magnetic flux Φ passing through the conductor cross-section increases. The following applies:

$$U_{\text{ind}} \sim \frac{d\Phi}{dt}.$$

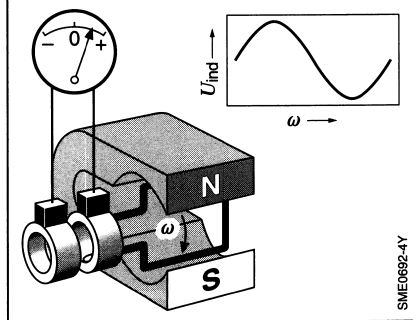
If the conductor loop consists not only of one turn but of n turns, this produces the n -fold induced voltage.

If the conductor loop rotates uniformly at the angular velocity ω the shape of the induced voltage is sinusoidal. The induced voltage can be tapped at the ends of the conductor loop via collector rings and carbon brushes. An alternating current flows when the circuit is completed.

The magnetic field for generating the induced voltage (excitation field) can be generated by permanent magnets. The

Figure 1: Generation of an induced voltage in a coil permeated by a magnetic field

U_{ind} Induced voltage,
 ω Angular velocity.



advantage of these is that, thanks to the simplicity of their design, they do not have to be technically sophisticated. This solution is used in small alternators (e.g. bicycle dynamos). The disadvantage of excitation using permanent magnets is that it cannot be regulated.

A excitation field capable of being regulated can be generated with an electromagnet. An electromagnet consists of an iron core and a winding (excitation winding), through which an excitation current is passed. The number of windings determines, together with the magnitude of the excitation current, the magnetic field strength. The magnetizable iron core in the electromagnet conducts the magnetic field generated by the coil. By altering the excitation current, it is possible to adjust the magnetic field and with it the magnitude of the induced voltage.

When an external power source (e.g. a battery) supplies the excitation current, this is referred to as external excitation. When the excitation current is tapped directly from the generated alternator current inside the alternator, this is referred to as self-excitation.

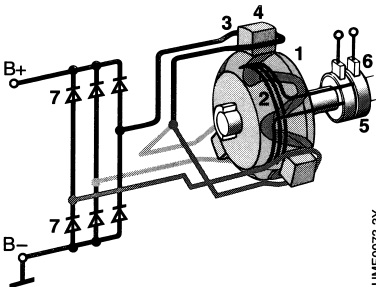
Alternator design

The essential components of an alternator are the three- or multi-phase armature windings and the excitation system (Figure 2). Because the design of the armature-winding system is more complex than that of the excitation system and the currents generated in the armature winding are much greater than the excitation current, the armature windings are accommodated in the stationary stator – also called the frame (stator winding). The magnet poles with the excitation winding (rotor winding) are located on the rotating part, the rotor (inductor). The rotor's magnetic field is generated as soon as an excitation current passes through this winding. The alternator must feature a high number of pole pairs so that it can generate a high induced voltage already at low speeds. A high number of poles generates a high response per rotation and thus a high induced voltage. This is the prerequisite for a high alternator output.

By applying the claw-pole principle, the magnetic field of a single field coil can be split in such a way that the required 12 to 16 poles or 6 to 8 pole pairs are created (Figure 2 and Figure 3). The number of poles that can be realized is limited. A low number of poles results in low machine utilization, while a high number of poles greatly increases the magnetic dispersion losses. These alternators are therefore designed depending on the power output as 12-pole or 16-pole machines.

Figure 2: Basic design of a claw-pole alternator with collector rings

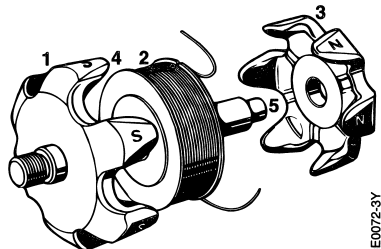
- 1 Rotor, 2 Exciter winding (rotor winding),
 - 3 Armature winding (stator winding),
 - 4 Stator, 5 Collector rings, 6 Brushes,
 - 7 Rectifier diodes.
- B+ Battery positive terminal,
B- Battery negative terminal.



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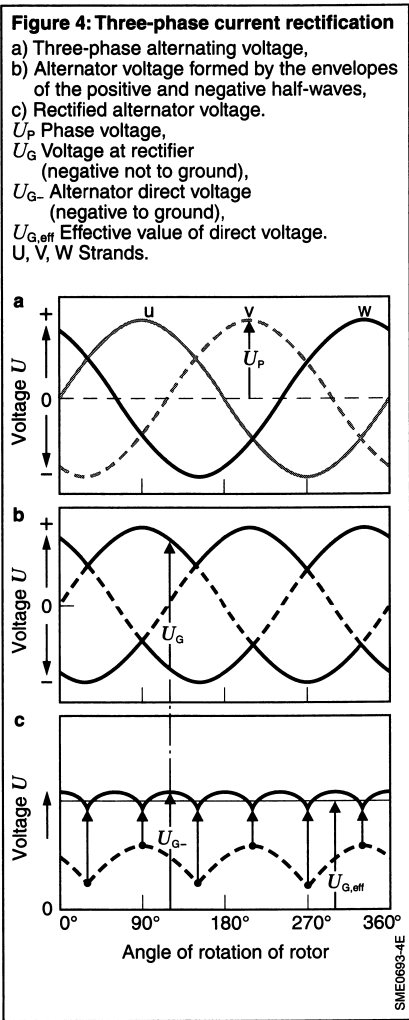
Figure 3: Components of a 12-pole claw-pole rotor

- 1 A-side (drive-end) claw pole,
- 2 Field coil,
- 3 B-side claw pole,
- 4 Chamfer on claw-pole-finger edge,
- 5 Alternator shaft.



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In the alternator, the armature contains three or more identical windings (phases) which are spatially offset in relation to one another (Figure 2). Because of the spatial offset of the windings, the sinusoidal alternating voltages generated in them are likewise out of phase with one another (temporally offset, Figure 4). The resulting alternating current is called three-phase current.



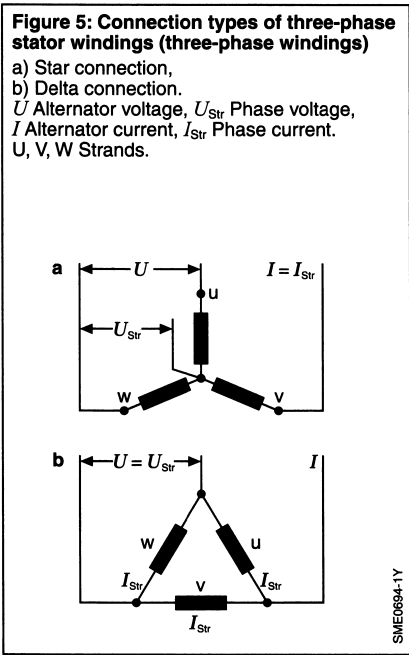
Alternator circuits

In three-phase alternators, six current leads would be needed to transmit electrical energy in the case of non-connected windings. This number can be reduced to three by linking the three circuits. The circuits are linked in a star connection (Figure 5a) or in a delta connection (Figure 5b). The winding starts are usually designated u, v, w and the winding ends x, y, z .

In the case of a star connection, the ends of the three winding phases are interconnected at a single point, the star point. Without a neutral conductor the sum total of the three currents to the star point is zero at every moment.

Rectification of alternating voltage

The alternating voltage generated by the alternator must be rectified, since direct current is required to supply the battery and the electronics in the vehicle electrical system.



Two power diodes are connected to each phase – one diode on the positive side which is usually connected via the positive heat sink of the rectifier to the B+ stud and one diode on the negative side which is connected via the negative heat sink of the rectifier to the alternator casing (B–terminal) (Figure 2). The alternator casing is also electrically connected to vehicle ground via the alternator mounting points. The positive half-waves are conducted by the diodes on the positive side (B+ stud), the negative half-waves by the diodes on the negative side (vehicle ground). This principle is called full-wave rectification (Figure 4).

Full-wave rectification of the three phases with the so-called B6 bridge circuit brings about the addition of the positive and negative envelope curves of these half-waves to a rectified, slightly rippled alternator voltage.

The direct current which the alternator delivers under electrical load via terminals B+ and B– to the vehicle electrical system is not smooth, but slightly rippled. This ripple is further smoothed by the battery in parallel with the alternator and, if necessary, by capacitors in the vehicle electrical system.

In the case of alternators where the stator winding is star-connected (Figure 5a), two additional diodes (therefore also called “supplementary diodes”) rectify the positive and negative half-wave of the star point. By rectifying the third harmonic in the phase voltages, these supplementary diodes can increase the alternator output current at 6,000 rpm by up to 10 %. Alternator efficiency is thus significantly improved in the upper speed range. In the lower speed range, the amplitude of the third harmonic is below the vehicle system voltage such that the supplementary diodes cannot deliver any current. Supplementary diodes are rarely used in modern-day alternators.

Instead of high-blocking-capability power diodes, modern-day motor-vehicle alternators use Zener diodes to rectify the alternating voltage. Zener diodes limit the high-energy voltage peaks to levels which are harmless for the alternator and the regulator (load-dump protection). In addition, Zener diodes can be used to provide remote protection for other voltage-sensitive

equipment in the vehicle electrical system. When using a 14 V alternator, the response voltage of a rectifier fitted with Zener diodes ranges from 25 to 30 V.

Reverse-current block

The rectifier diodes in the alternator serve not only to rectify the alternator voltage, but also to prevent the battery from discharging via the stator windings. If the engine is stopped or if the engine revs are so low (e.g. starting speed) that the alternator is not yet excited, without diodes a battery current would flow through the stator winding. The diodes are polarized with regard to the battery voltage in the reverse direction so as to prevent the flow of any significant battery discharge current. Current can therefore only flow from the alternator to the battery.

Generally, alternators are not provided with polarity-reversal protection. Reversal of battery polarity (e.g. mixing up the battery poles when using an external battery to start the vehicle) can lead to destruction of the alternator diodes and poses a threat to the semiconductor components of other devices.

Alternator electric circuits

The standard version of an alternator has three electric circuits:

- pre-excitation circuit (external excitation by battery current),
- excitation circuit (self-excitation),
- main circuit.

Pre-excitation circuit

Before self-excitation of the alternator can start, a voltage must be induced in the stator which can drive the excitation current. The rotor does also have a low residual magnetism (remanence) in the unenergized state, but this is not sufficient for self-excited operation. The alternator must therefore be externally excited at the start of operation. This is done via the pre-excitation circuit, which is supplied by the battery.

Previously the pre-excitation current was generated with pre-excitation diodes from the battery. Now that the multifunction regulator is used to regulate voltage, these pre-excitation diodes are no longer needed. When the multifunction regulator (see Volt-

age regulation) receives the information "ignition on" via connection L (Figure 6), it switches on the pre-excitation current with the permanently set on/off ratio (approximately 20 %, "controlled pre-excitation"). As soon as the rotor is turning, the regulator detects a voltage signal at phase connection V, and from its frequency it can derive the alternator speed. When the switch-on speed set in the regulator is reached, the regulator switches through the output stage completely (on/off ratio 100 %) so that the alternator starts to supply current to the vehicle electrical system.

Excitation circuit

The purpose of the excitation current I_{err} is to generate a magnetic field in the rotor's excitation winding during the alternator's entire operating period and thereby induced in the stator windings the required alternator voltage. Since alternators are self-excited generators, the excitation current is branched from the stator winding. Alternators with multifunction regulators acquired the excitation current directly from

terminal B+ (Figure 6). The excitation current flows through the rectifier's power-plus diodes via the multifunction regulator, the carbon brushes, collector rings, and the rotor winding to ground (B-).

Main circuit

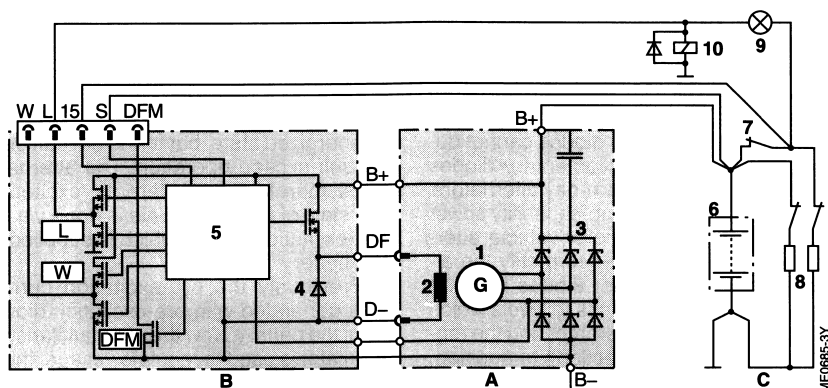
The alternating voltage induced in the alternator's phases must be rectified by the bridge circuit fitted with power diodes and directed to the battery and the electrical loads/consumers.

The alternator current I_G flows from the three windings via the power diodes to the battery and to the loads/consumers in the vehicle electrical system. The alternator current is divided into the battery charging current and into the consumer current.

Figure 6: Alternator

A Alternator, B Alternator regulator, C Vehicle electrical system.

- 1 Stator with armature windings, 2 Rotor with excitation winding, 3 Rectifier diodes,
- 4 Free-wheeling diode, 5 Regulator logic, 6 Battery, 7 Driving switch, 8 Loads/consumers,
- 9 Alternator indicator lamp,
- 10 Relay (switches equipment which is to be switched on only when alternator is active),
- DF Dynamo field, DFM (DF monitoring), L Lamp connection,
- W Digitized speed signal (alternator phase) for speed evaluation,
- S Scythe (supply lead, battery voltage),
- B+ Battery positive, B- Battery negative, D- Chassis ground,
- 15 Terminal 15.



Voltage regulation

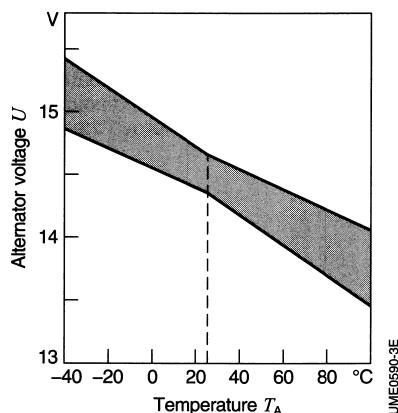
Function of voltage regulation

At constant excitation current, the alternator voltage is dependent on the alternator speed and load. The function of voltage regulation is to keep the alternator voltage – and thus also the vehicle system voltage – constant over the full speed range of the vehicle engine, irrespective of electrical load. To this end, the voltage regulator regulates the extent of the excitation current and consequently the magnitude of the magnetic field in the rotor depending on the voltage generated in the alternator. In this way, the regulator keeps the vehicle system voltage constant and prevents the battery from being overcharged or discharged during vehicle operation (see also Voltage regulation, Conventional vehicle electrical systems).

Vehicle electrical systems with 12 V battery voltage are regulated in the 14 V tolerance zone, those with 24 V battery voltage in the 28 V tolerance zone. As long as the voltage generated by the alternator is below the control voltage, the voltage regulator does not switch and the regulator output stage is switched on (on/off ratio 100 %).

Figure 7: Regulator characteristic curve

Permissible tolerance band of the alternator voltage (14 V) as a function of the alternator intake-air temperature T_A .



The regulator characteristic curve (alternator voltage as a function of temperature) is adapted to the chemical properties of the battery. At low temperatures the alternator voltage is slightly higher to improve the battery charge in winter. The input voltages of the electronic devices are taken into consideration here. At higher temperatures the alternator voltage is lower so as to avoid battery overcharging and gassing in summer. An example of a characteristic curve is shown in Figure 7. The voltage level is 14.5 V with a gradient of -10 mV/K (temperature compensation).

Principle of voltage regulation

If the voltage exceeds the upper setpoint value, the regulator switches off the output stage for activating the rotor winding. Driven by the inductance of the field coil, the excitation current initially flows on via the free-wheeling diode connected in parallel to the rotor winding; excitation becomes weaker and as a result the alternator voltage decreases. If now the alternator voltage drops below the lower setpoint value, the regulator switches on the excitation current again. Excitation increases and with it also the alternator voltage. If the voltage exceeds the upper setpoint value again, the regulation cycle begins afresh. Since the regulation cycles are in the range of milliseconds, the mean alternator-voltage value is well regulated to the specified characteristic curve (Figure 7).

The ratio of the respective on- and off-times is decisive for the magnitude of the mean excitation current. At low rotational speeds the on-time is relatively long and the off-time short. The excitation current is only interrupted for a short time and its mean value is high. Conversely, at high rotational speeds the on-time is short and the off-time long. A low excitation current flows.

During switch-over to the "Off" regulation state a voltage peak is created during interruption of the excitation current by self-induction in the rotor winding. To prevent the creation of such voltage peaks, a free-wheeling diode is connected in the regulator in parallel to the rotor winding. It takes over the excitation current at the moment of interruption and causes the "tailing off" or "extinction" of the current.

Regulators

Voltage regulators were formerly produced using discrete components. Today they incorporate hybrid or monolithic circuits (Figure 6). When monolithic technology is applied, the control and regulator IC, the power transistor, and the freewheeling diode are all accommodated on a single chip.

Multifunction regulators

Multifunction regulators perform special functions in addition to the task of voltage regulation described above. These multifunction regulators are today fitted in all new compact alternators. They draw the excitation current directly from B+ so that no excitation diodes are required.

Additional functions of the multifunction regulator as against conventional regulators are:

- controlled pre-excitation,
- detection of “alternator turning” by means of phase-connection monitoring,
- emergency regulation in the event of line interruption at connection L,
- overtemperature protection by limiting the excitation current when the limit temperature is exceeded,
- load-response functions.

For the “load-response function” (LR) a distinction is made between LR Driving and LR Start. LR Driving brings about a slow correction of the excitation current after an electrical-system load has been cut in so that the engine has sufficient time at idle to compensate the alternator’s rising drive torque. LR Start means that the alternator is inactive for a specific period after starting so that the engine can settle to a stable idle.

The power loss of the alternator indicator lamp in the instrument panel is frequently too great and disruptive. It can be reduced for example by transferring to an LED display. Multifunction regulators permit the activation of both bulbs and LEDs as display elements.

Intelligent alternator regulation

Voltage regulators with digital interfaces are the response to increased demands for greater mutual compatibility between engine-management and alternator-regulation systems. Various interfaces (e.g. bit-synchronous interface or LIN interface) are used here depending on the vehicle manufacturer.

The control voltage can be adjusted via the regulator interface. If a low control voltage is set, this results in low or no alternator output. The power input and the torque input at the alternator shaft decrease to low levels. On the other hand, the alternator voltage can be stepped up via the interface so that the alternator charges the battery and supplies the electrical equipment in the vehicle electrical system.

Because the alternator converts mechanical energy into electrical energy, the power input at the alternator shaft increases as the electrical power output increases. The internal-combustion engine needs more fuel to cover the alternator’s power requirement. However, if the alternator voltage is stepped up in overrun phases, the energy tapped by the alternator at the crankshaft does not cost any additional fuel, because overrun fuel cutoff stops the fuel supply. When the driver presses the accelerator pedal, the engine ECU steps down the alternator voltage again with the aid of the communication interface to the regulator in order to relieve the strain on the engine by the alternator torque. This process is also known as intelligent alternator regulation and recuperation.

Interface regulators allow a fine-tuning of load-response functions to engine operating state, optimization of torque patterns to reduce fuel consumption, and adjustment of charging voltage to improve the battery charge state.

Characteristic alternator values

Alternator performance

Automotive alternators function through the constant transmission ratio to the engine in a large rotational-speed range. Characteristic curves reflect the characteristic performance of an alternator. The alternator full-load characteristic refers here to a constant alternator voltage and to a defined ambient temperature.

Current characteristic

Defined rotational-speed points of the alternator are considered to describe the current characteristic (Figure 8).

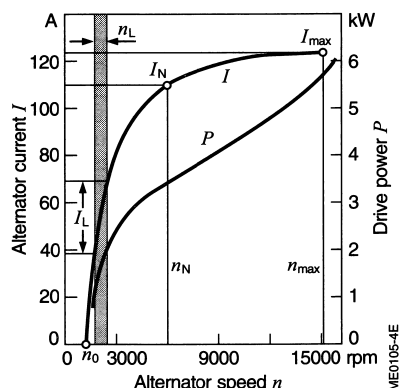
Self-excitation speed

The alternator can only deliver current to the vehicle electrical system when the induced voltage U_{ind} in the stator windings is greater than the sum total of the two diode forward voltages and the vehicle system voltage applied to B+ and B-. Because the induced voltage

$$U_{\text{ind}} \sim \frac{d\Phi}{dt}$$

Figure 8: Typical characteristic curve of an alternator

n_L Idle speed (dependent on transmission ratio),
 n_{max} Maximum speed, n_0 Zero-ampere speed,
 n_N Rated speed,
 I_L Current at engine idle, I_{max} Maximum current,
 I_N Rated current.



is dependent on the frequency of the change in flux, i.e. on the rotor speed, there is a speed range between zero and the "self-excitation speed" in which the alternator delivers no current (Figure 9).

Zero-ampere speed

The zero-ampere speed (n_0) is the rotational speed of the alternator at which the nominal voltage is reached without supplying current (approximately 1,000 rpm). Only at higher speeds can the alternator supply current.

Rotational speed and current at engine idle

The alternator speed at engine idle depends on the alternator's transmission ratio in relation to the engine. For compact-diode alternators this is defined at $n_L = 1,500$ rpm, for compact alternators accordingly to the usually higher transmission ratio at $n_L = 1,800$ rpm.

The current generated by the alternator at engine idle speed (idle current) must at least be enough to supply the permanently switched-on loads/consumers.

Rated speed and rated current

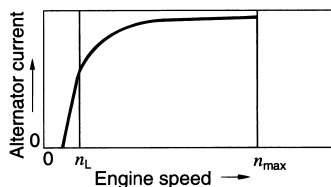
The full-load current which the alternator outputs at the rated speed $n_N = 6,000$ rpm, at the alternator voltage $U_G = 13.5$ V, and at ambient temperature $T_U = 23$ °C is referred to as rated current.

Maximum speed and maximum current

The alternator current rises sharply under full-load conditions as the speed increases.

Figure 9: Characteristic curve of maximum alternator current at constant voltage

n_L Idle speed,
 n_{max} Maximum speed.



The maximum current $I_{\max}$ is the highest current that can be generated by the alternator.

At higher speeds the voltage drop at the magnetizing reactance X_h (Figure 10) and the leakage reactance X_o becomes so great that, in spite of an increasing induced voltage, the current fails to rise significantly. The magnetizing reactance is obtained from that part of the coil inductance which generates the profitable induced voltage and whose flux takes the envisaged paths in the rotor and the stator. The leakage reactance forms that part of the flux which is not linked to the rotor – i.e. leakage fields which short, for example, in the end winding or directly via the groove.

The alternator's speed is first and foremost limited by its design (see Conditions of service).

Characteristic of drive power

The characteristic of drive power is used to design the drive belt. The characteristic shows by way of the engine speed range what power (maximum) is transmitted by the engine to the alternator. It is also possible to determine the alternator's efficiency from its drive power and power output. The characteristic of driver power exhibits a flat shape in the middle speed range and rises sharply at higher speeds.

Operating conditions

Rotational speed

The utilization of an alternator (generable energy per kilogram of mass) increases as the speed increases. It is therefore necessary to aim for as high a transmission ratio as possible between the crankshaft and the alternator. The alternator already outputs at least a third of its rated power when the engine is at idle speed. However, it is important to ensure that at maximum engine speed the maximum permissible alternator speed is not exceeded. Widening of the claw poles and the service life of the ball bearings used determine the maximum permissible speed of motor-vehicle alternators.

Typical values for the maximum speed are for compact alternators in the range of 18,000 to 22,000 rpm, for compact-diode alternators in the range of 15,000 to 18,000 rpm, and for alternators for commercial vehicles between 8,000 and 15,000 rpm. The transmission ratio is in the passenger-car sector between 1:2.2 and 1:3, and in the commercial-vehicle sector up to 1:5. Thanks to the possibility of adapting the alternator speed by means of a transmission ratio to the engine speed, the battery can be kept in a good state of charge even in adverse conditions (high proportion of idle phases, low outside temperatures).

Cooling

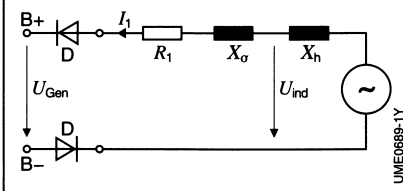
The losses arising during conversion from mechanical to electrical energy results in the alternator components being heated. The surrounding air in the engine compartment is used to cool the majority of the motor-vehicle alternators used today. If the surrounding air is not sufficient to cool the alternator, fresh-air induction from cooler areas or liquid cooling are suitable measures for cooling the components adequately.

Engine vibrations

The alternator can, depending on the mounting conditions and the vibration characteristic of the engine, be exposed to vibration accelerations of 500 to 800 m/s². The mountings and the components of the alternator are thereby subjected to

Figure 10: Simplified diagram of a phase with rectification

B+ Battery positive terminal,
B- Battery negative terminal,
D Rectifier diodes,
 I_1 Alternator current,
 R_1 Ohmic resistance,
 X_o Leakage reactance,
 X_h Magnetizing reactance,
 U_{ind} Induced voltage,
 U_{Gen} Alternator voltage.



high forces. Critical natural frequencies in the alternator assembly must therefore be avoided at all costs.

Engine-compartment climate

The alternator is exposed to splash water, dirt, oil and fuel mist, and where necessary road salt (grit). The alternator must be protected against corrosion so as to prevent the formation of any creepage paths between live parts.

Acoustic behavior

The stringent demands placed on the noise emissions of modern-day vehicles and the superior smooth running of modern-day internal-combustion engines require quiet alternators. As well as chamfers on the claw-pole fingers which reduce the hard chopping of the magnetic flux at finger edges, there are other possibilities for reducing the noise magnetically generated by motor-vehicle alternators. The following may be used: firstly, five phases in a pentagram connection (Figure 11), and secondly, two three-phase systems which electrically offset by 30°.

Interference-suppression measures

The alternator and also other electrical loads/consumers of a motor vehicle can interfere with other electrical and electronic devices through their electromagnetic fields. Intensified interference suppression of alternators is then necessary if a radio installation, a car phone, a car radio, etc. is operated in the immediate vicinity of or in the vehicle itself. Alternators are therefore as a rule fitted with a suppression capacitor. On older compact-diode alternators a suppression capacitor can be subsequently mounted to the outside of the collector-ring end shield. On compact alternators it is already integrated in the rectifier.

Efficiency

The ratio between the power which is supplied to the unit and the actual power output is known as the efficiency. Losses are an unavoidable byproduct of all processes in which mechanical or kinetic energy is converted into electrical energy. The losses in the claw-pole alternator are categorized as follows (Figure 12).

Losses in the claw-pole alternator

Copper losses in the stator and rotor windings

The ohmic losses in the stator windings and the rotor winding are called copper losses. They are proportional to the square of the current.

Iron losses in the laminated stator core

Iron losses result from hysteresis and eddy currents produced by alternating magnetic fields in the iron of the stator.

Eddy-current losses on the claw-pole surface

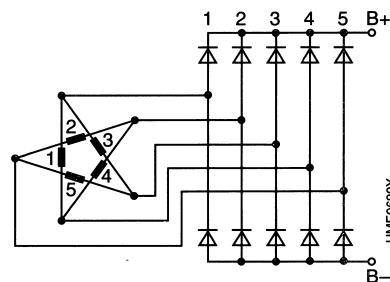
Eddy-current losses on the claw-pole surface are caused by fluctuations in flux brought about by the stator slotting.

Rectifier losses

Rectifier losses are caused by the voltage drop at the diodes. Rectifier losses can be reduced and thus efficiency improved by

Figure 11: Pentagram-connected five-phase stator winding with connected bridge rectifier as measure for improved acoustic behavior

B+ Battery positive terminal,
B- Battery negative terminal.



using semiconductors with a lower voltage drop, e.g. high-efficiency diodes (HEDs).

Mechanical losses

Mechanical losses include friction loss in the rolling bearings and at the sliding contacts, air resistance encountered by the rotor and, above all, fan resistance which rises dramatically as speed increases (aerodynamic losses).

Efficiency optimization

In regular automotive operation, the alternator operates in the part-load range. Efficiency at medium speeds is then 70 to 80 %. The use of a larger (and heavier) alternator allows it to operate in a more favorable part-load efficiency band for the same electrical load. The efficiency gains provided by the larger alternator more than compensate for losses in fuel economy associated with greater weight. However, the higher mass moment of inertia in the belt-drive system must be taken into consideration.

Alternator versions

Claw-pole alternators have completely replaced the direct-current generators previously used as standard in motor vehicles. Based on equal outputs for both concepts, a claw-pole alternator weighs 50 % less, and is also less expensive to manufacture. Large-scale application (at the beginning of the 1960s) only became feasible with the availability of compact, powerful, inexpensive, and reliable silicone diodes.

Design criteria

Different basic designs have been developed for the various conditions of service and performance ranges of the respective vehicle types and their driving engines. The following criteria are crucial to the choice of alternators:

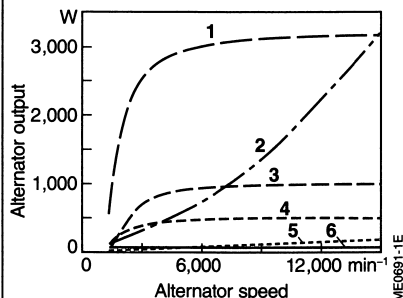
- vehicle type,
- operating conditions,
- rpm range of the respective internal-combustion engine,
- battery voltage of the vehicle electrical system,
- power demand of the loads/consumers,
- strain of the alternator by environmental influences (heat, dirt, etc.),
- installation conditions and dimensions.

Derived from these criteria is the required electrical dimensioning of the alternator, i.e.

- the alternator voltage (14 V or 28 V),
- the maximum power output (voltage $\times$ current intensity),
- the maximum current.

Figure 12: Loss distribution of a 220 A alternator

- 1 Alternator power output,
- 2 Iron losses,
- 3 Copper losses in the stator,
- 4 Rectifier losses,
- 5 Friction losses,
- 6 Copper losses in the rotor winding.



Compact alternator

The alternator casing consists of the drive end shield and the collector-ring end shield (Figure 13), between which the stator is mounted. The rotor shaft is mounted in the two bearing halves. The alternator stator consists of laminations provided with slots which are pressed together into a fixed laminated core. The turns of the three-phase stator winding are embedded in the slots.

The rotor gives the claw-pole alternator its name: It consists of two oppositely polarized pole-wheel halves whose claw-like pole fingers mesh alternately as south and north poles (Figure 2 and Figure 3).

The pole-wheel halves cover the ring-coil-shaped rotor winding, which is located on the pole core (Figure 3). The rotor winding receives the excitation current via carbon brushes (Figure 2) which are mounted in the collector-ring end shield and pressed by springs against the collector rings.

The magnetic working flux passes through the pole core, the left pole half and its fingers, across the air gap to the fixed laminated stator core with the stator winding, and returns through the right pole-wheel half back to the pole core to complete the circuit.

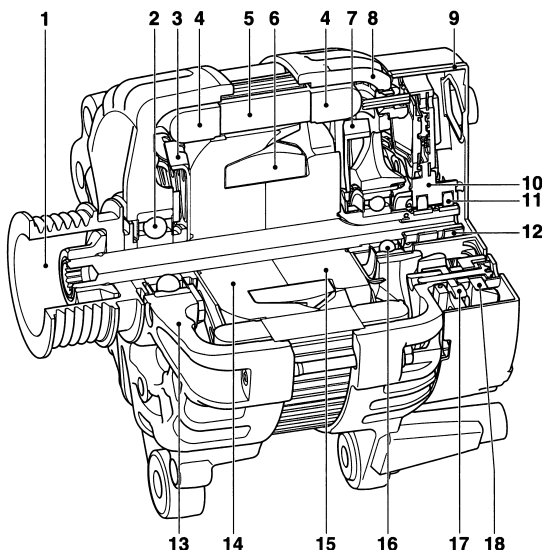
The compact alternator is cooled by two fans which are mounted at the drive and collector-ring end on the rotor. The fans draw in the cooling air in each case at the end face and discharge the heated air radially (double-flow ventilation). The two small fans produce substantially less aerodynamic noise than the large fan of a compact-diode alternator. They are also suitable for higher rotational speeds (maximum speed: 18,000 to 22,000 rpm). These two properties provide for a higher transmission ratio between the crankshaft and the alternator so that compact alternators can output up to 25 % more power for the same engine speed and size.

The belt pulley for the drive is also mounted on the rotor shaft. The alternator rotor can be operated in both directions of rotation. Based on the direction of rotation the fan shape must be designed for clockwise or counterclockwise rotation.

The electronic voltage regulator forms together with the brush holder a single unit if it is intended for mounting directly on the alternator. In some cases on commercial vehicles the electronic voltage regulator is mounted separately from the alternator.

Figure 13: Bosch EL Series (Efficiency Line) compact alternator

- 1 Belt pulley,
- 2 A-side (drive-end) ball bearing,
- 3 A-side fan,
- 4 Stator winding heads,
- 5 Laminated stator core,
- 6 Rotor winding (excitation winding),
- 7 B-side fan,
- 8 B-side end shield (collector-ring end shield),
- 9 Protective cap,
- 10 Brush holder,
- 11 Carbon brush,
- 12 Collector ring,
- 13 A-side end shield (drive end shield),
- 14 A-side claw pole,
- 15 B-side claw pole,
- 16 B-side ball bearing,
- 17 Negative heat sink of rectifier,
- 18 Positive heat sink of rectifier.



at a protected point on the body and connected via electrical plug-in connections to the brush holder.

The compact alternator is used as standard in passenger cars, but is also used in the commercial-vehicle sector. Depending on the requirement, the EL Series (Efficiency Line), the NBL Series (New Base Line), or the PL Series (Power Density Line) is used.

Compact-diode alternator

The compact-diode claw-pole alternator (Figure 14) differs from the compact alternator first and foremost in the form of the large fan which is located between the belt pulley and the pot-shaped alternator casing. The external fan with a maximum speed of 12,000 to 18,000 rpm draws the cooling air axially through the casing (single-flow ventilation).

Because the rectifier, regulator, and brush/collector-ring system are arranged

inside the end shield, the shaft inside the collector rings must be relatively thick to be able to transmit the belt-drive forces to the external ball bearing. The collector rings therefore have a large diameter, only permitting a limited brush service life.

Compact-diode alternators can still be found in older vehicles and in commercial vehicles.

Double-T1 alternator

The Double-T1 alternator consists of two electrically and mechanically coupled T1-size alternators in a common casing.

The electronic voltage regulator is installed inside the alternator. Between D+ and D- there is a 100-watt resistor which causes the alternator indicator lamp to light up in the event of an open-circuit field.

The Double-T1 alternator is used in buses that impose high power demands on the alternator due to rising comfort requirements.

Alternators with windingless rotors

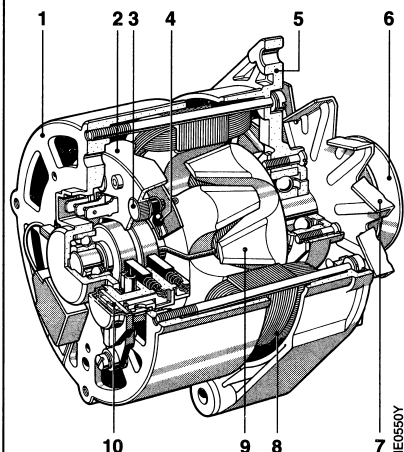
The windingless-rotor alternator is a special design variant of the claw-pole alternator where only the claw poles rotate, while the rotor winding remains stationary. With this design, the regulator supplies directly to the rotor winding; sliding contacts are not required.

The rotating parts consists merely of the rotor with pole wheel and conductive element. The conductive element consists as a rule of a magnetically highly permeable material (e.g. soft iron), which boosts the magnetic flux of a magnetic field acting on the conductive element or forwards it (e.g. to the stator core). Six pole fingers of the same polarity in each case form a pole-finger crown as north and south poles. Only one of the two pole-finger crowns is connected directly to the rotor shaft. A non-magnetic retaining ring, which is located below the meshing pole fingers, holds the two crowns together as claw-pole halves.

The magnetic flux passes from the pole core of the rotating fan via the fixed internal pole to the conductive element, then across its pole finger to the fixed stator core. The magnetic circuit is completed in the rotor pole core via the oppositely polarized claw half.

Figure 14: Compact-diode alternator

- 1 Collector-ring end shield,
- 2 Rectifier heat sink,
- 3 Power diode,
- 4 Excitation diode,
- 5 Drive end shield with mounting flanges,
- 6 Belt pulley,
- 7 External fan,
- 8 Stator,
- 9 Claw-pole rotor,
- 10 Transistor regulator.



The magnetic flux must when compared with the collector-ring rotor overcome two additional air gaps between the rotating pole wheel and the fixed internal pole.

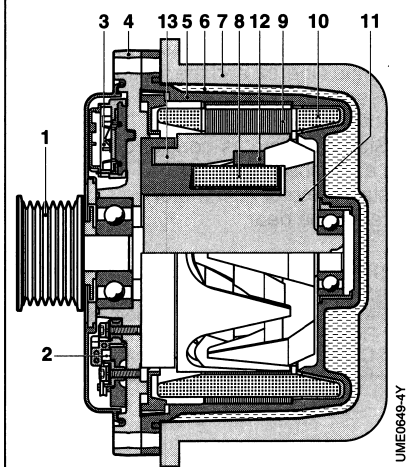
Thanks to the omission of the wear component collector-ring/carbon system, these alternators are particularly suitable for applications which require a long service life combined with heavy alternator load, e.g. for construction machinery or traction generators. The units weigh somewhat more than claw-pole alternators with collector rings due to the fact that additional iron and copper is required to conduct the magnetic flux through two additional air gaps.

Liquid-cooled alternator

The windingless rotor is also used in liquid-cooled alternators (Figure 15), among other applications. In the case of this alternator, engine coolant flows around the complete jacket and rear of the alternator casing. This significantly reduces noise when compared with air-cooled alternators in that the alternator is completely encapsulated and no fan produces aerodynamic noise. The electronic components are mounted on the drive end shield.

Figure 15: Liquid-cooled alternator with windingless rotor

- 1 Belt pulley, 2 Rectifier, 3 Regulator,
- 4 Drive end shield, 5 Alternator casing,
- 6 Coolant jacket,
- 7 Jacket casing for engine mounting,
- 8 Stationary rotor winding,
- 9 Stator core, 10 Stator winding,
- 11 Windingless rotor,
- 12 Non-magnetic intermediate ring,
- 13 Conductive element.



Starting systems

Starter

Overview

Internal-combustion engines in motor vehicles require start assistance to start. They must be cranked by a starter at a minimum speed before they can supply sufficient energy in sustained operation from the combustion cycles to cover the torque requirements for the compression and gas-exchange cycles. During starting the mass inertia and the friction and compression resistances of the engine must be overcome.

Starting systems consist of the following assemblies (Figure 1)

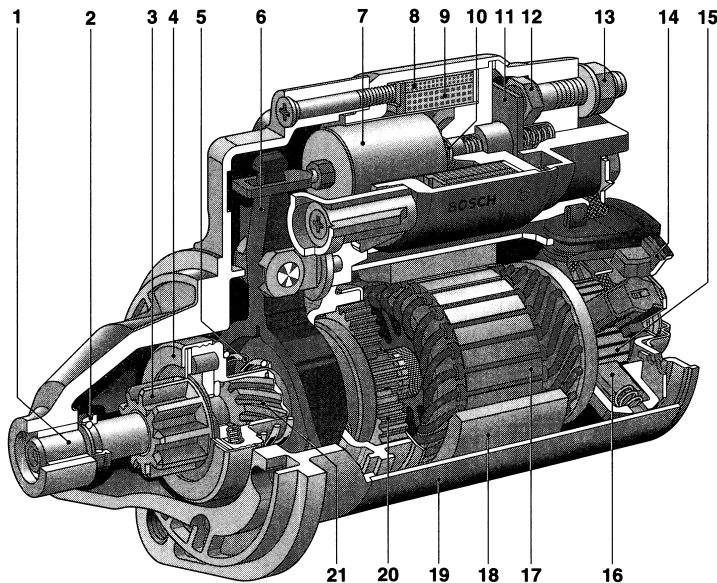
- starter motor (DC motor),
- reduction gear,

- solenoid switch,
- overrunning clutch (starter pinion, roller-type overrunning clutch),
- switchgear and control units,
- battery, and
- wiring.

The starter torque is transmitted via the starter pinion and the engine-flywheel ring gear to the engine. To start, the starter pinion engages the ring gear. The ring gear with typically 130 teeth (103 to 144 on passenger cars, 110 to 160 on commercial vehicles) is mounted on vehicles with manual transmission on the engine flywheel and on vehicles with automatic transmission on the converter housing. The starter pinion with typically 10 teeth

Figure 1: R70 reduction-gear starter

1 Drive shaft, 2 Stop ring, 3 Starter pinion with sloping teeth, 4 Roller-type clutch, 5 Meshing spring, 6 Engagement lever, 7 Solenoid switch, 8 Hold-in winding, 9 Pull-in winding, 10 Return spring, 11 Contact bridge, 12 Contact, 13 Terminal, 14 Commutator bearing, 15 Commutator, 16 Carbon brush, 17 Starter armature, 18 Magnets, 19 Pole housing, 20 Reduction gear (planetary gear), 21 Involute helical spline with helical teeth.

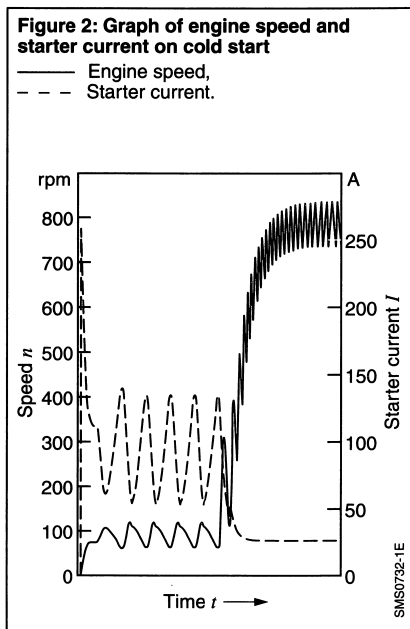


(8 to 10 on passenger cars, 9 to 13 on commercial vehicles) is only a few millimeters away from the ring gear in its initial position.

Requirements

Because of the high transmission ratio between the starter pinion and the ring gear, the starter may be designed for high speeds and low torque. This allows the dimensions and the weight of the starter to be kept small. The transmission ratio is in the range of 1:10 to 1:20, enabling the speeds required for sustained engine operation (gasoline engines 60 to 100 rpm; diesel engines 80 to 200 rpm) to be achieved.

Compression and decompression in the cylinders means that the torque required to turn the engine over fluctuates considerably, as a result of which the momentary engine speed also fluctuates considerably. Figure 2 shows a typical graph for engine speed and starter-motor current on cold start.



The starter itself must satisfy the following technical requirements:

- readiness to function at any time,
- sufficient starting power at different temperatures,
- high service life,
- robust design,
- low weight and low dimensions,
- maintenance-free operation.

Influencing factors

To achieve the air/fuel (A/F) mixture necessary for sustained operation of gasoline engines and the auto-ignition temperature for diesel engines, the starter must drive the internal-combustion engine at a minimum speed (cranking speed). The cranking speed largely depends on the characteristics of the internal-combustion engine (engine type, engine swept volume, number of cylinders, compression, bearing friction, engine oil, fuel-management system, additional loads driven by the engine), and the ambient temperature.

In general, starting torque and starting rotational speed require a gradual increase in starting power as temperatures decline. However, the power supplied by a starter battery falls as temperatures drop because its internal resistance increases. This opposing relationship of electrical load requirements and available power means that the least favorable operating conditions which a starting system must be capable of dealing with is a cold start.

Because of the high current draw of a starter motor, the voltage drop occurring on the supply lead significantly influences the performance characteristics of the starter motor.

Classification

Passenger-car starting systems are equipped with a rated power of up to 3.0 kW at a rated voltage of 12 V. These can start gasoline engines with up to approximately 7 liters engine displacement and diesel engines with up to approximately 3 liters.

Commercial-vehicle starting systems come with 12 V and 24 V nominal voltage. In Europe 24 V systems with rated power of between 3.0 kW and 14.0 kW are customary, enabling diesel engines of up to 30 liters displacement to be started

in single operation and up to 60 liters displacement in double parallel operation.

Starters may be classified by the following criteria according to their technical type:

- type of power transfer: direct starter or reduction-gear starter,
- type of magnetic field generation in electric motor: permanent-magnet starter or electrically excited starter,
- type of engagement: sliding-gear, Bendix or pre-engaged-drive starter.

Permanently excited pre-engaged-drive starters with reduction gear are predominantly used in the automobile these days. These combine the benefit of a high starting power with a compact size.

Starter design and operation

A starter (Figure 1) essentially consists of the electric motor and the engaging system with solenoid switch, starter pinion, roller-type overrunning clutch, and meshing spring. The engaging system ensures that the starter pinion meshes with the ring gear. From a starter output of approximately 1 kW a reduction gear is integrated in the starter which reduces the speed of the DC motor. In the case of the direct starter the starter pinion is driven at the starter-motor armature speed.

During the start, the starter pinion engages with the ring gear by means of solenoid switch (starter relay) when the driving switch is operated. The starter pinion drives the internal-combustion engine via the ring gear until the engine

can run at sustained operation. After the engine starts, it can accelerate quickly to high rotational speeds. After only several ignitions, the engine accelerates so powerfully that the starter can no longer match its speed. The internal-combustion engine "overruns" the starter motor and would then accelerate the electric-motor armature to extremely high speeds if the overrunning clutch installed between the starter pinion and armature did not cancel the non-positive lock.

Starter motor

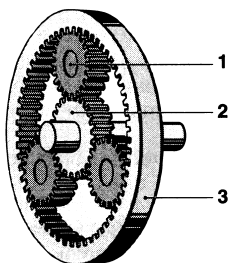
The starter motor is a conventional DC motor. The predominant design for a starter motor is the 6-pole design. The magnetic materials available today have allowed the development of starters which are resistant to demagnetization, and have a highly effective magnetic flux to deliver a high starting power. As the magnetic field is generated by a permanent magnet, and the retroactive effect of the armature magnetic field is very minor, excitation is practically constant over the entire operating range.

Reduction gear

The objective of starter development is to minimize the weight and dimensions of the starter by reducing the volume of the electric motor etc. In order to achieve the same starting power at the same time, a higher armature speed is required to compensate for the existing lower armature torque. The torque is adjusted to match the rotation rate of the internal-combustion engine crankshaft by increasing the overall gear ratio of crankshaft to starter armature. This is achieved with the assistance of an additional gear stage (reduction gear), which is incorporated into the starter. This usually takes the form of a planetary gear on passenger-car and commercial-vehicle starters. It comprises a sun gear mounted on the armature shaft, a planetary-gear carrier normally with three planet gears and a fixed internal ring gear (Figure 3). The spur-toothed planetary gear transfers the armature torque via the starter drive shaft to the starter pinion free from transverse forces. The high armature speed here (15,000 to 25,000 rpm) is stepped down at a ratio of $i \approx 3$ to 6.

Figure 3: Planetary gear

1 Planetary gear, 2 Sun gear,
3 Internal ring gear.



UTA0003-2Y

The standard is a plastic internal ring gear made from fiber-reinforced polyamide. Depending on requirements, a sintered steel internal ring gear with additional damping elements may also be used as an alternative.

Planetary gears have the advantage of a very compact design with large transmission ratios. With favorable gear-meshing geometry, high torques can be transferred with low noise generation. Facing outwards these gears are free from transverse forces such that the bearings of the armature shaft and the drive shaft are subject only to low forces even with high power outputs.

Solenoid switch

The starter current is up to 1500 A for passenger cars and up to 2500 A for commercial vehicles. Since contacts for such high currents are subjected to high loads, it is essential to use a power relay. The relay is actuated by a relatively low control current (relay current, approximately 30 A for passenger cars, approximately 80 A for commercial vehicles). For switching it is sufficient to have a mechanical switch (driving switch, start button) or a simple minirelay which is actuated by the engine ECU (see Automatic starting systems).

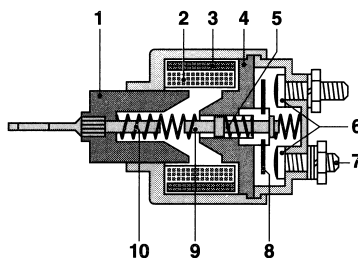
The solenoid switch used in the starter (Figure 4) consists of a switch housing, switch armature, magnetic core, contact carrier (contact bridge, contact spring), a pull-in winding and a hold-in winding, return spring, and a switch cover with integrated connections. The solenoid switch has to fulfill two functions:

- It advances the starter pinion over the engagement lever into the ring gear and
- switches the main starter current by closing and opening the contact bridge.

In order for the switch armature to ensure the movement of the starter pinion over the engagement travel, a switch current of approximately 30 A is required to generate the necessary magnetic force. If the switch armature is fully pulled in (air gap equals zero), significantly less magnetic excitation and hence a lower switch current is required (approximately 8 A) to hold the switch armature in the end position. The winding is divided into a pull-in winding and a hold-in winding, above all in order to limit heating of the switch winding. Electrically, the two windings are connected in parallel (Figure 5), which means

Figure 4: Solenoid switch

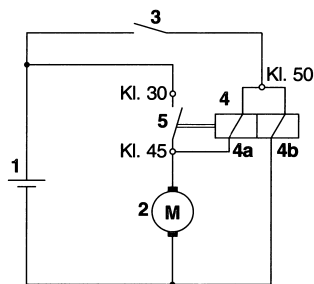
- 1 Switch armature, 2 Pull-in winding,
- 3 Holding-in winding, 4 Magnetic core,
- 5 Contact spring, 6 Contacts,
- 7 Electrical connection, 8 Contact bridge,
- 9 Armature shaft (divided), 10 Return spring.



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Figure 5: Solenoid-switch circuit

- 1 Battery, 2 Starter, 3 Driving switch,
- 4 Solenoid switch,
- 4a Pull-in winding, 4b Hold-in winding,
- 5 Contact bridge.

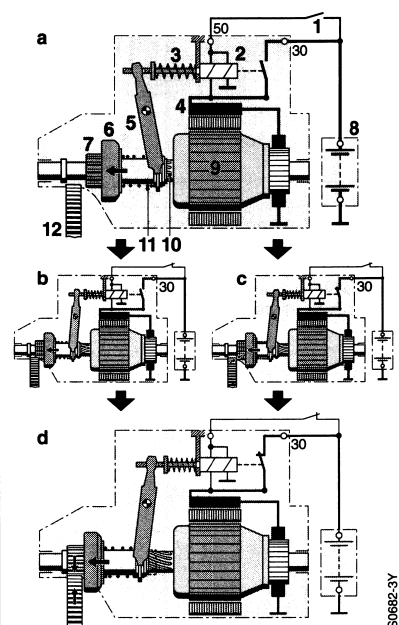


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that the magnetic excitations of the two windings add together. The start of the two windings are both applied to terminal 50 of the solenoid switch. The winding end of the pull-in winding is connected via the starter armature, that of the hold-in winding is connected directly to the ground potential.

Figure 6: Working phases of a pre-engaged-drive starter

- a) Rest position,
 - b) Tooth on gap,
 - c) Tooth on tooth,
 - d) Engine is cranked.
- 1 Ignition/starting switch (driving switch),
 - 2 Solenoid switch,
 - 3 Return spring,
 - 4 Excitation winding (series winding),
 - 5 Engagement lever,
 - 6 Roller-type overrunning clutch,
 - 7 Starter pinion,
 - 8 Battery,
 - 9 Armature,
 - 10 Helical spline,
 - 11 Meshing spring,
 - 12 Engine-flywheel ring gear.



When a voltage is applied to terminal 50 (ignition switch in start position) of the solenoid switch, the switch armature is pulled axially into the housing by the magnetic force generated by the pull-in winding and hold-in winding. This movement pushes the starter pinion forwards by the engagement lever towards the ring gear (Figure 6). Only once the switch armature is almost completely pulled in is the contact bridge closed and the main starter current switched on. This prevents the starter motor beginning to rotate before the starter pinion has engaged in the ring gear. As the two winding ends for the pull-in winding are now connected to positive, current flows only in the hold-in winding. The lower magnetic force of the hold-in winding is sufficient to hold the switch armature securely until the ignition/starting switch is opened.

The starter's electrical connections (term. 50, term. 30, and term. 45) are combined on the solenoid-switch cover to form an assembly. The switch cover usually consists of a duroplastic material which ensures the required mechanical load capability even at high thermal loads (briefly up to 180 °C).

Meshing of the pre-engaged-drive starter

The pre-engaged-drive starter has become a worldwide standard for the passenger car, as secure operation over the entire operating range is guaranteed with this engagement principle. On pre-engaged-drive starters, the engagement travel is made up of a lever-travel phase and a helical-travel phase. The switch armature attracts, against the force of a return spring, the engagement lever, which in turn pushes the driver of the overrunning clutch with the starter pinion via the helical spline against the internal-combustion engine's ring gear (lever travel). At the same time these parts are induced to rotate slightly by the effect of the helical spline. The starter armature still does not rotate in this phase as the main current for the excitation and armature windings is not yet switched on.

If a pinion tooth meshes directly with a tooth gap on the ring gear (tooth-gap positioning) when the starter pinion meets the ring gear, the starter pinion engages

as far as the movement of the relay allows (Figure 6). The slight rotary motion of the starter pinion induced by the helical spline makes this meshing process easier.

If the starter-pinion tooth strikes a tooth on the ring gear (tooth-tooth positioning) when the starter pinion meets the ring gear – this occurs approximately 80 % of the time – the switch armature tensions the meshing spring via the engagement lever, as the starter pinion can travel no further axially. The starter pinion is thus pressed with increasing force against the ring gear. The meshing spring considerably reduces the wear in the starter-pinion/ring-gear area by limiting the axial force, thus increasing the service life and reliability of the system.

Once the pinion travel limit generated by the solenoid switch has been reached, the contact bridge of the switch armature closes and the starter armature begins to rotate. In the case of tooth-gap positioning, the rotating electric motor screws the starter pinion fully into the ring gear via the helical spline (helical travel). The helical spline creating the helical travel also ensures that the starter pinion can only transfer the full torque of the starter once it has reached the stop (end of helical travel). This ensures that the teeth of the starter pinion and ring gear are not mechanically overloaded.

Starting from a tooth-tooth position, the electric motor turns the starter pinion in front of the ring gear until a pinion tooth finds a tooth gap in the ring gear. The pretensioned meshing spring then pushes the starter pinion and overrunning clutch forward. The rotating electric motor screws the starter pinion fully into the ring gear via the helical spline. The ground sloping teeth at the front on the starter pinion makes the meshing process easier and reduces wear.

When the switch winding is de-energized, the return spring pushes the switch armature – and the starter pinion and overrunning clutch via the engagement lever – back into the rest position. The overrunning torque caused by the friction of the overrunning clutch generates an axial force in conjunction with the helical spline, which supports the starter-pinion's demeshing process.

The pull-in and hold-in windings must have the same number of turns. Otherwise the relay could lock during the de-activation process whereby the two windings connected in succession would be supplied backwards via terminal 45. The same numbers of turns ensure that the magnetic fields of the coils now passed through in opposite directions counterbalance each other and the relay switches off safely.

Meshing of the sliding-gear starter

Sliding-gear starters are used to start large internal-combustion engines. Because the requirements on service life are generally significantly higher for commercial vehicles, the engagement process usually takes place in two stages in order to protect the starter pinion and ring gear. The first stage starts the engagement of the starter pinion in the ring gear, while in the second stage, the starter pinion is softly meshed in the ring gear. The starter pinion may be rotated to resolve tooth-on-tooth positions by mechanical or electrical means.

Overrunning clutch

In all starter designs, the drive torque is transmitted by an overrunning clutch (overriding clutch). This overrunning clutch is installed between the starter and the starter pinion. Its purpose is to drive the starter pinion while the starter is cranking the internal-combustion engine, and then release the connection between the starter pinion and drive shaft as soon as the internal-combustion engine is turning faster than the starter.

Overrunning clutches for starters are non-positive (roller-type and multiplate clutches) or positive (radial-tooth clutch) in design.

Roller-type overrunning clutch

Roller-type overrunning clutches are normally used on the pre-engaged-drive starters being considered here. The "roller-type overrunning clutch" assembly comprises the driver with clutch shell, the roller race, the rollers, the springs, the starter pinion, the pinion shaft with helical spline, and an end cap (Figure 7). The driver with clutch shell is connected

via the helical spline to the drive shaft. The non-positive connection between the internal cylindrical pinion shaft with the helical teeth and the outer-rotating clutch shell of the driver is established by cylindrical rollers which can move on the roller race.

In the rest state the springs press the rollers into the narrowing part between the clutch-shell race and the pinion shaft. The clamping angle that forms at the rollers is chosen so small that the starter pinion is rotated immediately when the starter starts up.

When the overrunning operation is initiated, the rollers are moved by the friction at the pinion shaft against spring force into the widening part of the race, whereby the rollers on account of the spring force are constantly in contact without play with the pinion shaft and race. The overrunning torque that develops is relatively small and has a significant effect on the starter-armature idle speed that is obtained.

Radial-tooth overrunning clutch

The radial-tooth overrunning clutch is installed in conjunction with mechanical two-stage meshing in some sliding-gear starters for commercial vehicles. This overrunning clutch transmits the torque positively via radial tooththing.

Multiplate overrunning clutch

The multiplate overrunning clutch is used in larger sliding-gear starters for commercial vehicles. The non-positive connection

between the motor armature and the starter pinion is established by a ring-shaped plate pack.

Demeshing

The solenoid switch drops out as soon as the driver releases the driving switch. The return spring presses the switch armature back, as a result of which initially the primary-current contact opens and the starter current is interrupted. The demeshing spring completes the retraction of the starter pinion, disengaging it from the ring gear. Demeshing is here supported by the rotary motion of the starter pinion as it returns over the helical spline. The starter freewheels to a standstill and the entire mechanism returns to its initial position.

Switch-off function

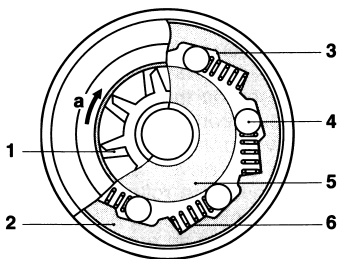
The switch armature is connected to the engagement lever in such a way that there is a certain amount of free travel or "play". If the engine fails to achieve sustained operation (e.g. due to lack of fuel), the starting sequence must be aborted. At this point, the starter pinion and the ring gear are under full load and the starter pinion is fully engaged.

When the switch current is switched off, there must be sufficient switch-armature free travel to allow it to open the primary-current contacts. If this were not the case, the engagement lever would hold the switch armature in place. The primary-current contact would remain closed and it would not be possible to abort the start.

On commercial-vehicle starters the geometrical constraints dictate that a cut-out spring be used to deliver the switch-off function instead of the free-travel arrangement. The force of this spring when the starter pinion is in its initial position overcomes the force of the switch-armature return spring and push the armature back against the stop on the lever. When the switch armature is pulled in, the armature return-spring force must in turn be sufficiently large to compress the cutout spring to such an extent that the contact bridge lifts off from the contact studs.

Figure 7: Overrunning clutch

- 1 Starter pinion, 2 Clutch shell,
 - 3 Roller race,
 - 4 Roller, 5 Pinion shaft,
 - 6 Spring.
- a Direction of rotation.



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Configuration of a starter

The most important boundary conditions which must be taken into consideration in the configuration of a starter are:

- The minimum starting temperature, i.e. the lowest motor temperature at which a start must still be possible.
- The resistance to rotation of the engine, i.e. the required torque at the crankshaft including all supplementary loads.
- The requirement minimum engine speed at the minimum starting temperature.
- The transmission ration between the starter and the crankshaft.
- The nominal voltage of the starting system.
- The properties of the starter battery.
- The resistance of the supply leads between the battery and the starter and the contact resistances of terminals and switching elements (isolating switches, etc.).
- The starter's speed/torque characteristic.
- The maximum permissible voltage dip in the vehicle electrical system at which the operating capability of the engine electronics is still guaranteed.

In view of these boundary conditions, the starter cannot be considered in isolation. As an integral part of the overall system of engine including its ancillaries, the vehicle electrical system with battery and cabling as well as the starter itself, the starter must be matched to the other components.

Triggering the starter

Conventional control

During conventional starts, the driver connects the battery voltage (driving switch in starting position) to the starter solenoid switch. The switch current generates in the solenoid switch the switch force which on the one hand moves the starter pinion towards the engine ring gear and on the other hand switches on the starter's primary current.

The starter is switched off at the ignition switch, which opens and interrupts the starter-relay voltage.

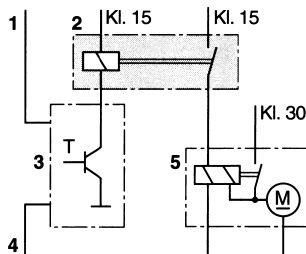
Automatic starting systems

The high demands on vehicles with regard to convenience, safety, quality, and low noise levels have resulted in an increase in the use of automatic starting systems. An automatic starting system differs from a conventional one by virtue of additional components (Figure 8): one or more ballast relays, as well as hardware and software components (e.g. an engine ECU) to control the starting sequence.

The driver then no longer directly controls the starter relays current; instead the ignition key is used to send a request signal to the control unit, which then performs a series of checks before initiating the starting sequence. The safety check

Figure 8: Automatic starting system (circuit diagram)

- 1 Starting signal from driver,
- 2 Ballast relay,
- 3 ECU,
- 4 Park-Neutral position or clutch signal,
- 5 Starter.



comprises a wide range of options and can verify any of the following:

- Is the driver authorized to start the vehicle (theft-deterrence feature)?
- Is the internal-combustion engine stationary (prevents the pinion from meshing with the moving ring gear)?
- Is the state of charge (in relation to engine temperature) sufficient to carry out the start?
- For automatic transmissions, is the selector lever in neutral or, for on manually shifted transmissions, is the clutch disengaged?

When the check has been completed successfully, the control unit initiates the start. On starting, the starting system compares the engine speed with a sustained operation speed of the engine (which may also depend on the engine temperature). Once the engine reaches sustained operation speed, the ECU switches the starter off. This always achieves the shortest possible starting time, reduces the noise levels, and lessens starter wear.

Start/stop system

Operation

An automatic starting system can also be used as the basis to implement start/stop operation. Here, the internal-combustion engine is switched off when the vehicle is not in motion taking into account defined temperature inputs and the state of charge of the battery, e.g. at traffic lights, and restarts automatically when required. The operation of a start/stop system – consisting of start/stop starter, ECU with start/stop function, electronic battery sensor, deep-cycle-resistant battery, pedals with sensors, alternator – presupposes a higher-level activation by means of which the switch-off and restart strategy is implemented.

A start/stop system requires an electrical energy management system that incorporates battery-charge detection. Measures may also be required to stabilize the vehicle electrical system during the starting phase to avoid unacceptable voltage drops. The control equipment and starting system must therefore be matched. The control units have to fulfill their function at a significantly lowered supply voltage.

Demands imposed on start/stop starters

One technical challenge is to optimize the rapid-starting performance of the respective internal-combustion engine (repeatable rapid starting). To be able to satisfy the demands with regard to service life and more rapid starting to reduce noise generation, the deep-cycle resistance of start/stop starters has been increased significantly compared with conventional starters. Furthermore, the design of the meshing mechanism including starter-pinion and ring-gear geometry has been wear- and noise-optimized.

At present reduction-gear starters for start/stop operation in conjunction with a high-quality ring gear achieve more than 200,000 starting cycles.

Wiring harnesses and plug-in connections

Wiring harnesses

Requirements

The purpose of the wiring harness is to distribute power and signals within a motor vehicle. A wiring harness in the present-day, mid-class passenger car with average equipment has approximately 750 different lines, their length totaling around 1500 meters (Table 1). In recent years, the number of contact points has practically doubled due to the continuous rise in functions in the motor vehicle. A distinction is made between engine-compartment wiring harnesses and between body, front-end, rear-end, cockpit, roof, door, and tank wiring harnesses (Figure 1, Table 2). Above all, engine-compartment wiring harnesses are subject to high temperature, vibration, and media loads.

Wiring harnesses have considerable influence on the costs and quality of a vehicle. The following points must be taken into consideration in wiring-harness development:

- imperviousness to dust and media,
- electromagnetic compatibility,
- temperatures,
- protection of the wires against damage,
- wire routing,
- ventilation of the wiring harness.

It is therefore necessary to involve wiring harness experts as early as in the system definition stage. Figure 2 shows a wiring harness that was developed as a special intake-module wiring harness. Thanks to the optimization of routing and security in conjunction with engine and wiring-harness development, it was possible to achieve an advancement of quality as well as to yield cost and weight advantages.

Dimensioning and selection of materials

The most important tasks for the wiring harness developer are:

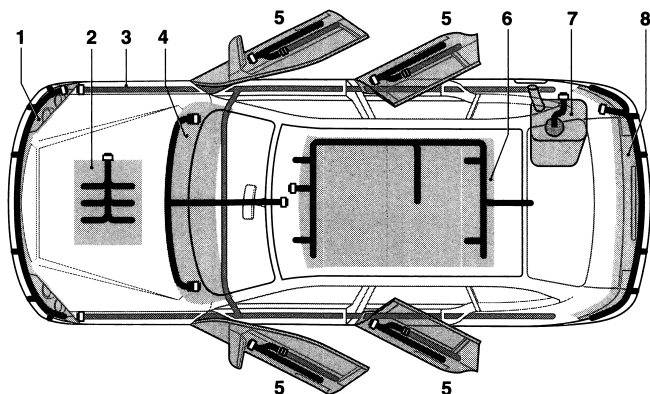
- dimensioning of line cross-sections,
- material selection,
- selection of suitable plug-in connections,
- routing of lines under consideration of ambient temperature, engine vibrations, acceleration and EMC,
- consideration of the environment in which the wiring harness is routed (topology, assembly stages in vehicle manufacture and equipment on the assembly line).

Line cross-sections

Line cross-sections are defined based on permissible voltage drops. The lower

Figure 1: Wiring-harness modules

- 1 Front end,
- 2 Engine compartment,
- 3 Body,
- 4 Cockpit,
- 5 Doors,
- 6 Roof,
- 7 Tank,
- 8 Rear end.



cross-section limit is determined by the line strength. Convention has it that no lines with a cross-section of less than 0.5 mm^2 are used. With additional measures (e.g. supports, protective tubes, tension relief), even a cross-section of 0.35 mm^2 may be permissible.

Table 1: Complexity of wiring harnesses (typical values for complete wiring harness)

	Small vehicle	Medium class	Luxury class
Number of plug connectors	70	120	250
Number of contact points	700	1500	3000
Number of wires	350	750	1500
Total length of wires in meters	700	1500	3200

Table 2: Data for wiring harnesses (typical values for vehicle with average equipment)

	Body wiring harness	Cockpit wiring harness
- Different modules	54	23
- Wires	528	57
- Twisted wires	24	24
- Total length (in meters)	1370	226
- Different contact parts	72	17
- Assorted components (e.g. plug housings, cable ducts, coverings)	227	63

Materials

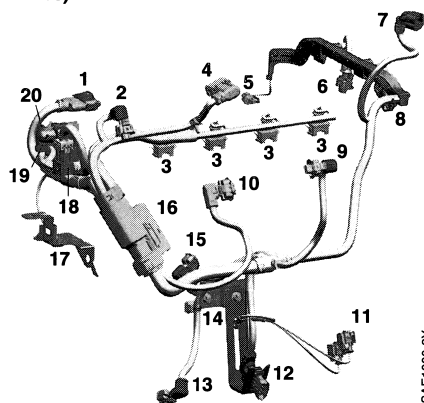
Copper is usually used as the conductive material on account of its high conductivity. Recent trends have involved the increased use of aluminum on account of its weight and cost advantages above all for line cross-sections greater than 2.5 mm^2 . The insulation materials for the lines are defined by the temperature to which they are exposed. It is necessary to use materials that are suitable for the high temperatures of continuous operation. Here, the ambient temperature must be taken into consideration as much as the heating caused by the flow of current. The materials used are thermoplastics (e.g. PE, PA, PVC), fluoropolymers (e.g. ETFE, FEP), and elastomers (e.g. CSM, SIR).

If the lines are not routed past particularly hot parts (e.g. exhaust pipe, exhaust-gas recirculation) in the engine topology, one of the criteria for the selection of the insulation material and the cable cross-section could be the derating curve of the contact with its associated line. The derating curve represents the relationship between current, the temperature increase that it causes, and the ambient temperature of the plug-in connection. It can be taken from the relevant technical customer documentation for the contact. Normally, the heat generated in the contacts can only be carried away along the lines themselves. What is also to be noted is that at high usage tempera-

Figure 2: Intake-module wiring harness (example of an engine-compartment wiring harness)

Connector for

- 1 Ignition-coil module, 2 Channel deactivation,
- 3 Fuel injectors, 4 Throttle device,
- 5 Oil-pressure switch,
- 6 Engine-temperature sensor,
- 7 Intake-air temperature sensor,
- 8 Camshaft sensor,
- 9 Canister-purge valve,
- 10 Intake-manifold pressure sensor,
- 11 Charge-current indicator lamp,
- 12 λ sensor downstream of catalytic converter,
- 13 Speed sensor,
- 14 Terminal 50, starter switch,
- 15 Knock sensor, 16 Engine ECU,
- 17 Engine ground,
- 18 Separable connector for engine and transmission wiring harnesses,
- 19 λ sensor upstream of catalytic converter,
- 20 Exhaust-gas recirculation valve.



tures ($>100\text{ }^{\circ}\text{C}$) the contact materials can give way to the applied mechanical stresses (metal relaxation). It is possible to influence the relationships described by means of larger line cross-sections and the use of suitable contact types and more noble surfaces (e.g. gold, silver) and thus higher limit temperatures. For highly fluctuating current intensities, it is often useful to measure the contact temperature on an application-specific basis.

Line routing and EMC measures

Lines should be routed in such a way as to prevent damage and line breaks. This is achieved by means of fasteners and supports for the wiring-harness branches. Vibration loads on contacts and plug-in connections are reduced by fastening the wiring harness as close to the plug as possible and at the same level as the vibration where possible. The line routing must be determined in close cooperation with the engine or the vehicle developer.

To avoid EMC problems, it is recommended to route sensitive lines and lines with steep current flanks separately, making maximum use of the available space. Shielded lines are not straightforward to produce and are therefore expensive. They also need to be grounded. The twisting in pairs of signal lines is a more cost-favorable and effective measure.

Line protection

Lines need to be protected against chafing and against making contact with sharp edges and hot surfaces. Adhesive tapes are used for this purpose. The level of protection is determined by the interval and winding density. Corrugated tubing (material savings from corrugation) with the necessary connecting pieces is often used as line protection. However, tape fixing is still an essential means of preventing movement of individual lines inside the corrugated tube. Optimal protection is offered by cable ducts.

Wiring harnesses are at risk from rodents. A remedy may be provided by rodent-resistant, extruded plastic tubing.

Plug-in connections

Function and requirements

Electrical plug-in connections must establish a reliable connection between different system components and thereby ensure the safe functioning of the systems under all operating conditions. They must be designed in such a way as to withstand the multitude of loads to which they are exposed over the entire service life of the motor vehicle. Examples of such loads are

- vibration loads,
- temperature fluctuations,
- high and low temperatures,
- humidity and moisture loads and splash water,
- aggressive liquids and corrosive gases, and
- micro-movement of the contacts with resulting fretting corrosion.

These loads can increase the contact resistances of the contacts up to the point of total interruption.

Even the insulation resistances can decrease and result in the short-circuiting of neighboring lines. Electrical plug-in connections must therefore exhibit the following properties:

- low contact resistances of the current-carrying parts,
- high insulation resistance between the current-carrying parts of different voltage potential,
- high imperviousness to water, moisture, and salt spray.

Aside from the physical properties, plug-in connections must satisfy further requirements for the area of application, such as

- easy, error-free handling in automotive assembly,
- safe reverse-polarity protection,
- secure and noticeable locking and easy unlocking,
- robustness and compatibility with automatic machine handling in wiring-harness production and transportation.

The high integration density of electronics in the motor vehicle places high demands on a car's plug-in connections. Not only do they carry high currents (e.g. activation of ignition coils), they also carry analog

signal currents with low voltage and current intensity (e.g. signal voltage of the engine-temperature sensor). Throughout the service life of the vehicle, the plug-in connections must ensure the reliable transmission of signals between ECUs and to the sensors and actuators.

The increasing demands of emission-control legislation and active vehicle safety are forcing the ever more precise transmission of signals through the contacts of the plug-in connections. Many parameters must be taken into account in the conception, design, and testing of a plug-in connection (e.g. environmental influences, imperviousness, contact forces, contact form, surface quality).

The most common cause of failure of a plug-in connection is wearing of the contact caused by vibrations or temperature change. The wear promotes oxidation. This results in an increase in ohmic resistance - the contact may, for example, be subjected to thermal overload. The contact part may be heated beyond the melting point of the copper alloy. In the case of highly resistant signal contacts, the vehicle controller often detects a plausibility error by comparison with other signals; the controller then enters fault mode. These problem areas in the plug-in connection are diagnosed by the on-board diagnostics (OBD) required by

emission-control legislation. However, it is difficult to diagnose the error in the service workshops because this defect is displayed as being a component failure. It is only possible to diagnose the faulty contact indirectly.

For the assembly of the plug-in connection, there are various functional elements on the plug housing intended to ensure that the cables with their crimped contacts can be joined to the plug-in connection reliably and defect-free. Modern plug-in connections have a joining force of less than 100 N so that the assembly operative is able to reliably join the plug to the component or ECU interface. The risk of plug-in connections being connected to the interface incorrectly increases with higher connecting forces. The plug would come loose during vehicle operation.

Design and types

Plug-in connections have different areas of application (Table 3). These are characterized by the number of pins and ambient conditions. There are four different classes of plug-in connection: direct engine attachment, attachment close to the engine, transmission attachment, and body attachment. Another difference is the temperature class of the installation location.

High-pin-count plug-in connections

High-pin-count plug-in connections are used for all ECUs in the vehicle. They differ in their number of pins and the geometry of the pins (Table 4). Figure 3 shows a typical design of a high-pin-count plug-in connection. An example of the mating component of the plug is pictured in Figure 4. The high-pin-count male connectors are usually soldered in or stitched in on the ECU board.

The complete plug-in connection is sealed against the plug connector of the associated ECU by a circumferential radial seal in the plug housing. This, together with three sealing lips, ensures a reliable seal against the ECU sealing collar.

The contacts are protected against the ingress of humidity along the cable by a flat seal, through which the contacts are inserted and the line crimped to them. A silica-gel mat or silica mat is used for this

Table 3: Uses of plug-in connections

	No. of pins	Special features	Application
Low-pin-count	1 to 10	No joining-force support	Sensors and actuators (many different requirements)
High-pin-count	10 to 300	Joining-force support by slide, lever, module construction	ECUs (several, similar requirements)
Special plugs	any	e.g. integrated electronics	Special applications (individual, matched requirements)

purpose. Larger contacts and lines may also be sealed using a single-core seal (see Low-pin-count plug-in connections).

When the plug is assembled, the contact with the line attached is inserted through the flat seal that is already in the plug. The contact slides home into its position in the contact carrier. The contact latches on its own by a locking spring that engages in an undercut in the plastic housing of the plug. Once all contacts are in their final position, a slide pin is inserted to provide a second contact safeguard, or secondary lock. This is an additional security measure and increases the retaining force of the contact in the plug-in connection. In addition, the sliding movement is a means of checking that the contacts are in the correct position.

The operating force of the plug-in connection is reduced by a lever and a slider mechanism. For this purpose the studs provided on the side of the plug shroud in Figure 4 are engaged by the slider links (Figure 3) when the plug is connected to the interface. When the lever mounted in the plug housing is repositioned, the slide is pushed via toothing transversely to the plug-in direction into the plug housing and uses the links on both sides to draw the plug into the interface by the studs.

Low-pin-count plug-in connections
Low-pin-count plug-in connections (Figure 5) are used for actuators (e.g. fuel injectors) and sensors. Their design is similar in principle to that of a high-pin-count plug-in connection. The operating

Table 4: Flat connectors (examples)

		Pin thickness in mm		
		0.4	0.6	0.8
Pin width in mm	0.5	x		
	0.6		x	
	1.2		x	
	1.5		x	
	2.8			x
	4.8			x

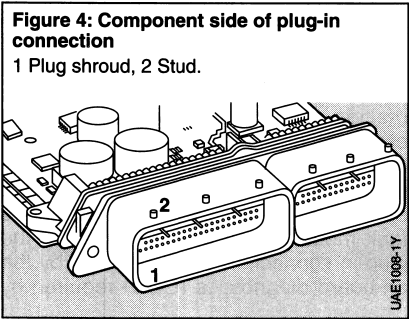
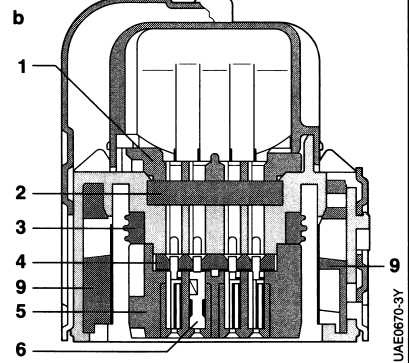
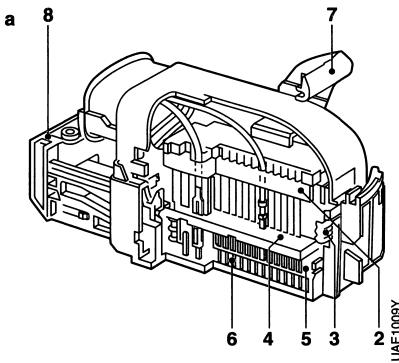


Figure 3: High-pin-count plug-in connection

- a) View, b) Cross-section.
1 Pressure plate, 2 Flat seal, 3 Radial seal, 4 Slide pin (secondary lock),
5 Contact carrier, 6 Contact, 7 Lever, 8 Slider mechanism, 9 Slider links.



force of the plug-in connection is not usually supported.

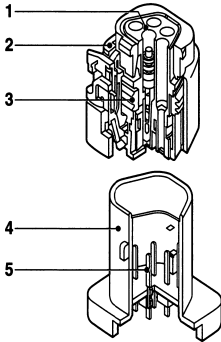
The connection between a low-pin-count plug contact system and the interface is sealed with a radial seal. Inside the plastic housing, however, the lines are sealed with single-core seals secured to the contact.

Contact systems

The electrical contact system inside a plug-in connection is formed as a rule by a jack (on the plug side) and a contact pin, or a flat blade, or a pin (on the component side).

Figure 5: Low-pin-count plug-in connection

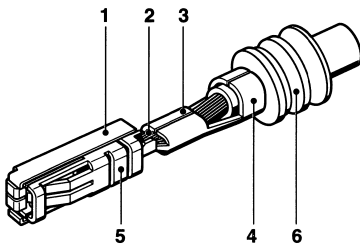
1 Contact carrier, 2 Housing,
3 Radial seal, 4 Interface, 5 Flat blade.



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Figure 6: Contact

1 Steel overspring, 2 Single core,
3 Conductor crimp, 4 Insulation crimp,
5 Meander, 6 Single-core seal.



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There are different type series for the various fields of use for Bosch plug-in connections. Depending on the conditions of use, the specially suited contacts are used in these. Figure 6 shows by way of example a two-part contact which is used in motor vehicles in components which are subject to particular vibration loads.

The inner part – the live part – is pressed from a high-quality copper alloy. It is protected by a steel overspring, which at the same time increases the contact forces of the contact by means of an inwardly acting spring element. A catch arm pressed out from the steel overspring engages the contact in the plastic housing part.

Contacts are coated with tin, silver or gold, depending on requirements. To improve the wear characteristics of the contact point, not only are different contact coatings used but also different structural shapes. Different decoupling mechanisms are integrated into the contact part to decouple cable vibrations from the contact point (e.g. meandering routing of the supply lead).

The cables are crimped onto the contact. The crimp geometry on the contact must be adapted to the cable concerned. Pliers or fully automatic, process-monitored crimping presses with contact-specific tools are available for the crimping process.

Electromagnetic compatibility

Requirements

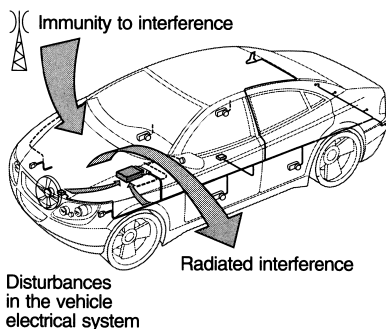
Electromagnetic compatibility (EMC) is the general term for the target state in which electrotechnical devices and state-of-the-art technologies (e.g. wireless systems) do not have unintended mutual interference from electrical, magnetic or electromagnetic effects.

Particularly in vehicle electronics, the importance of electromagnetic compatibility is increasing due to the higher amount of electrical equipment and the use of new technologies, such as electric and hybrid drives with new energy accumulators (e.g. high-performance batteries and fuel cells) on the one hand and mobile communication systems (e.g. phone, navigation and Internet) on the other. This leads to a rising level of complexity in today's automobiles (Figure 1).

Electronic power train systems installed in the vehicle (e.g. engine and transmission control, electric drive), safety systems (e.g. antilock braking system, driving-dynamics control system, and airbag), comfort and convenience electronics (e.g. climate control, electrical adjusting devices) and mobile communication sys-

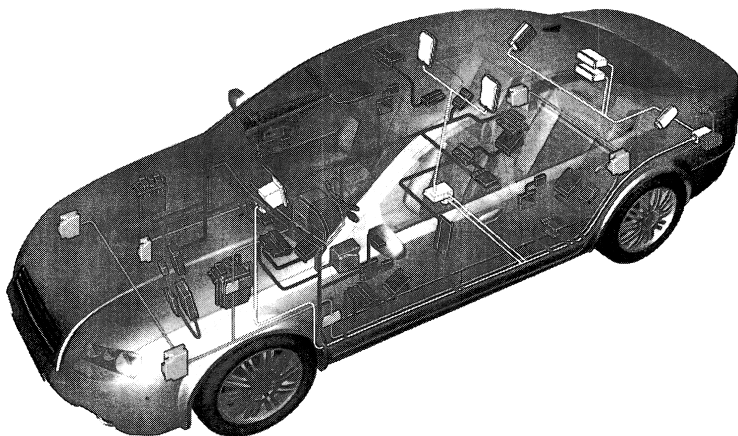
tems (e.g. radio, navigation, Internet) are arranged next to each other in close proximity. The associated high density and number of fast-switching, high-performance electronic components on the one hand and the requirements of today's communication on the other pose a great and, in part, new challenge to electromagnetic compatibility (Figure 2).

Figure 2: Electromagnetic compatibility in motor vehicles



UAE1204E

Figure 1: Electronic systems and wiring harness in a modern motor vehicle



UAE1203-1Y

Interference emission and interference immunity

Sources of interference in the DC vehicle electrical system

Ripple in vehicle electrical system

In a conventional vehicle with combustion engine, the alternator supplies the vehicle electrical system with rectified three-phase current. Although the current is smoothed by the vehicle battery, a residual ripple remains. In addition, the energy requirements of the electrical and electronic systems influence the DC voltage supply.

The amplitude of the ripple in the vehicle electrical system depends on the load on the vehicle electrical system and the wiring. Its frequency changes according to alternator speed and the consumer behavior. The fundamental oscillation is in the kilohertz range. It can penetrate the vehicle sound systems – either directly (conductive) or inductive – where the ripple is heard as a howl in the loudspeaker system.

Pulses in the vehicle electrical system

Voltage pulses are generated on the supply lines when electrical equipment is switched on and off. They are routed to adjacent systems directly through the power supply (through conductive coupling, Figure 3a) and indirectly by coupling from connecting lines (through inductive and capacitive coupling, Figure 3b and Figure 3c). These unwanted interference pulses can cause anything from malfunction to total destruction of the adjacent systems. The signal shapes and amplitudes acting as disturbance values depend on the configuration of the vehicle electrical system, such as the ground concept, the position of the wiring harnesses and the individual lines in the wiring harness.

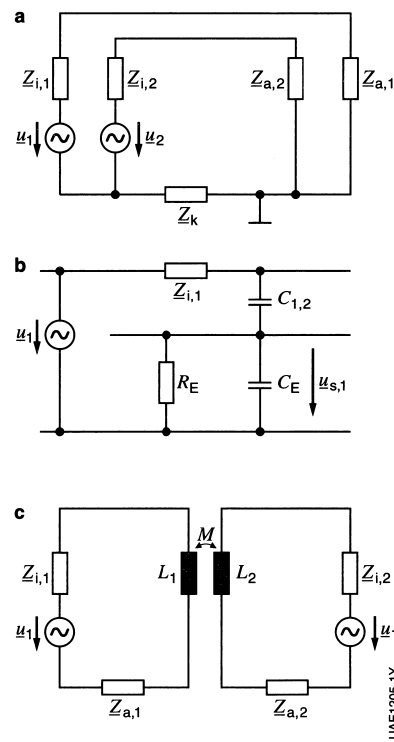
The wide variety of pulses that occur in the vehicle are classified into typical pulse shapes. Major parameters are pulse amplitude, signal rise and fall times as well as internal resistance of the pulse source. A suitable selection of permitted values for interference emission from the sources of interference and the required values for interference immunity ensures that there is no unintended behavior of the elec-

tronic systems without unnecessarily high effort for interference suppression. This can be done using various concepts. For example, a higher interference emission for the electric actuators and motors can be allowed than for typical pulse sources if the electronic components, such as control units and sensors, are designed with corresponding interference resistance.

Figure 3: Conductive, capacitive and inductive coupling

a) Conductive coupling of interference signals,
b) Capacitive coupling of interference signals,
c) Inductive coupling of interference signals.

Z_i Internal resistance (complex size),
 Z_a Terminating resistance (complex size),
 u_1, u_2 Voltage sources (complex size),
 u_s Interference voltage (complex size),
 R_E Input resistance,
 C_E Input capacitance,
 $C_{1,2}$ Capacitance between both conductors,
 L_1, L_2 Inductance of the conductors,
 M Inductive coupling,
 Z_K Coupling impedance.



Potentially susceptible devices

Electronic control units and sensors are potentially susceptible devices for interference signals that enter the vehicle electrical system from the outside (Figure 2). These interference signals come from the neighboring systems in the vehicle. Malfunctions occur when the system loses the ability to distinguish between interference signals and useful signals. The possibility of taking effective measures depends on the characteristics of useful and interference signals.

The control unit is unable to distinguish between useful and interference signals if the characteristic of an interference signal is similar to that of a useful signal – for instance, when a pulse-shaped interference signal is at the same frequency as the signal from a wheel-speed sensor. Critical frequencies are those in the range of useful signal frequencies ($f_S \approx f_N$) and a low multiple of a signal frequency.

Special feature in vehicle electrical systems with high voltages

High voltage and currents in motor vehicles with hybrid and electric drives pose new challenges. In addition to the contact protection required due to the high voltages, EMC is particularly important. In the components of the power electronics (e.g. inverter and DC/DC converter) and in the electrical machine, large interference signals can arise. Only by using shielding concepts along with suitable filter circuits can these interference signals be reduced enough to allow compliance with the required limit values for mobile communication in the vehicle.

Another special feature is the charging devices with their connections to the public power supply network. This interface, and the resulting requirements with regard to permitted interference emission into the public power grid and the necessary interference protection, must be taken into consideration in the overall design of vehicle electrical systems with high voltages.

High-frequency vibrations and oscillations in the vehicle electrical system

In addition to the low-frequency ripple in vehicle electrical systems and the pulses in these systems, high-frequency vibrations and oscillations are caused in many electromechanical and electronic components by switching operations. Examples include commutation operations in brush motors or in electronically commutated electric motors, activation of output stages or circuits in digital electronics (such as the CPU core of an electronic control unit). These oscillations can spread – more or less attenuated – into the vehicle electrical system via the connected lines, particularly the power supply lines, and can get into the systems for communications electronics via the power supply lines or the capacitive and inductive coupling in the wiring harness.

Depending on whether the measured spectrum of radio interference voltage has a more or less continuous curve or consists of discrete lines, we refer to it as broad-band interference or narrow-band interference. Broad-band interference is caused, for example, by electric motors in wiper drives, control systems, fans, fuel pumps or alternators, but also by certain electronic components. Narrow-band interference is caused, for example, by electronic control units with microprocessors. This allocation depends on the used bandwidth of the radio service under consideration or the bandwidth used during the measurement compared to the characteristics of the interference signal. The various interference signals also have various effects on analog and digital radio systems.

Disturbances can travel through the electric lines in the wiring harness to the supply and signal connections and into the connecting cables of the antennas. They can also be received by the antennas directly and, just like the desired useful signals, they can get into the receiver circuits of the mobile communication devices. These high-frequency disturbances can interfere with vehicle communication systems, because they are often found in the frequency and amplitude range of the useful signal. Narrow-band interference is

Figure 4: Time signal and spectrum for a trapezoidal pulse

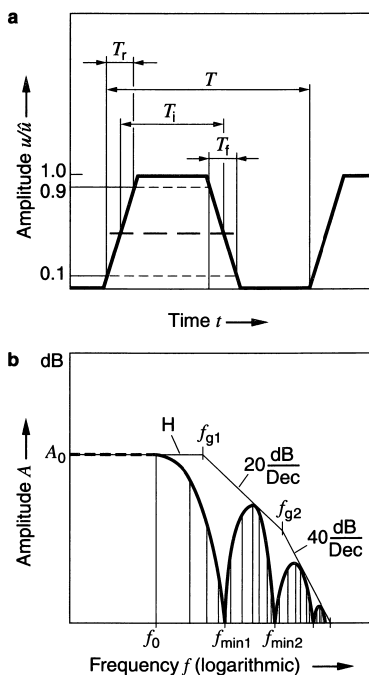
- a) Dependency on time,
 b) Dependency on frequency.
 T Period duration,
 T_r Rise time (from 10% to 90%),
 T_i Release time (from 90% to 10%),
 T_i Pulse duration,
 A_0 Amplitude,
 $\hat{u}$ Pulse amplitude,
 f_0 Basic frequency of the time signal,
 f_{n-1} Harmonics,
 $f_{\min}$ Periodic minimums,
 f_g Fundamental frequencies,
 k Pulse duty factor,
 n Number of the n th harmonic,
 m Number of lines between minimums,
 H Envelope,
 Dec Decade.

$$f_0 = \frac{1}{T}, \quad k = \frac{T_r}{T_i},$$

$$f_{n-1} = \frac{n}{T} = n f_0, \quad f_{\min} = \frac{n}{T_i},$$

$$f_{g1} = \frac{1}{\pi T_i}, \quad f_{g2} = \frac{1}{\pi T_r},$$

$$m = \frac{T}{T_i}, \quad A_0 = 2 \hat{u} T_i.$$



particularly critical, because it has signal characteristics that are very similar to the spectrum of transmitters (Figure 4).

Electrostatic discharge

The subject of potential danger to components and electronic circuits from electrostatic discharge (ESD) also belongs to the field of EMC. The task here is to protect components and equipment from interference or damage by static discharge from humans or from machinery (exposed components) during operation, production and maintenance. This involves both adopting appropriate methods for handling equipment and designing equipment in such a way that the voltages (up to several thousand volts) produced by electrostatic discharges are reduced to acceptable levels.

Immunity to interference from electromagnetic fields

Sources of interference and potentially susceptible devices

During operation, vehicles and their electronic equipment are exposed to various electromagnetic waves, for example from radio, television and wireless transmitters, which are operated at a fixed location, or even from within the same or a neighboring vehicle. Electronic circuits must not experience interference from the electromagnetic fields of the transmitters and the resulting, unwanted voltages and currents.

The large number of electric lines in the wiring harness as well as internal structures in devices (such as printed circuit boards in electronic control units or design technology and joining and bonding techniques in actuators) function as an antenna structure. Depending on their geometric dimensions and the electromagnetic wave frequencies, they receive transmitter signals and conduct them to the semiconductor components. Unmodulated and modulated high-frequency signals can be demodulated at the pn transitions in the semiconductor components. This can lead to level shifts caused by the direct component or to the superposition of transient interference signals as a result of demodulated LF components of the interference signal. The car-

rier frequency $f_{S, HF}$ is usually much higher than the useful-signal frequencies f_N . LF components of the interference signal are particularly critical if its frequency $f_{S, NF}$ is in the range of the useful-signal frequencies f_N . Interference signals with frequencies far lower than those of the useful signals can lead to disturbances due to intermodulations.

Electronic components must be designed in such a way that their function is not impaired by the externally generated interference signals in the electronic circuits.

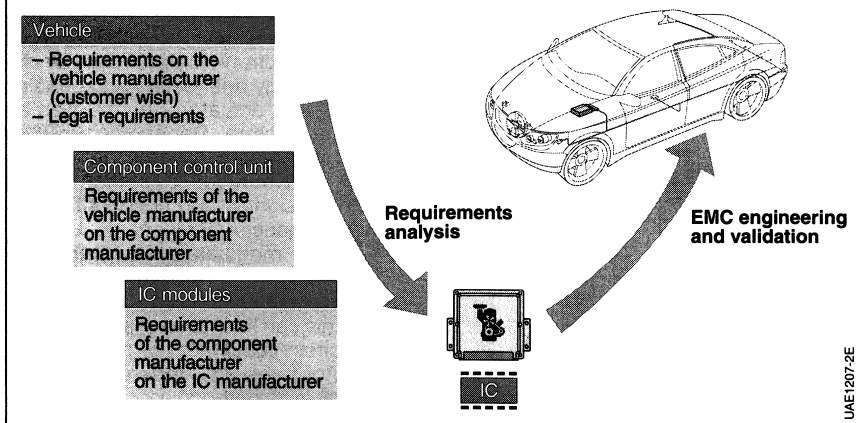
EMC-oriented development

The importance of EMC-oriented development in automotive electronics is increasing at all levels (see V model). Nowadays, safeguarding of EMC in vehicles influences the design of semiconductor components and of modules (including suitable design technology and the joining and bonding techniques of integrated circuits for components and systems) as well as the configuration of the entire vehicle. Thus EMC-oriented design is an integral part of a state-of-the-art development process at all levels. Today, retroactively suppressing interference is usually no longer possible or, at the very least, extremely time consuming and costly.

EMC requirements analysis

When development of a new electronic system for a motor vehicle begins, necessary requirements must first be analyzed and codified in the customer specifications (Figure 5). In addition, the vehicle manufacturer compiles EMC requirements documents, which take into account legal requirements and expectations of vehicle customers. These EMC specifications contain the requirements for vehicles and the resulting requirements for electric systems and components that are being installed in the vehicles. From these requirements, the system or

Figure 5: Requirements analysis and EMC development based on the V model



component manufacturer derives its own requirements for components and specifies requirements for design elements, electronic wiring and semiconductor components. Finally, IC and component manufacturers derive from this the requirements for their own products.

EMC development and verification

During the development stages, these requirements must be defined immediately at all levels in the customer specifications (Figure 5, see also V-model) and taken in to account early on during the vehicle design stage (e.g. the wire harness configuration and its position in the vehicle, power supply and ground concept, and the installing point of electronic components). The requirements derived from the vehicle must be taken into account, keeping in mind the system and component design (e.g. system topology, circuit design, housing design, circuit board layout, design and joining and bonding techniques). Similarly, the component manufacturer takes into account the EMC requirements during the IC and filter design stages. During the development process, the effectiveness of individual development steps is verified, in which various prototypes are metrologically assessed or variant studies using numerical simulation methods are implemented.

EMC validation

During the closing stages of EMC development, the requirements set out in the functional specifications and resulting customer specifications are validated in order to prove their worth. This validation is typically carried out using standardized test methods in accordance with legal mandates, standards and EMC specifications for component and vehicle manufacturers. The measurements to be carried out, operating statuses used and limit values to be observed are written down in test plans and the results are documented in a qualification report.

EMC measuring techniques

EMC measuring techniques are an important tool with regard to EMC-compliant development. Through the use of suitable test methods, the effectiveness of design standards like a selection of suitable semiconductor components, circuit design, circuit board layout, design and housing design are drafted and checked. On the other hand, the EMC test methods used in assessing are conducive to complying with EMC and legal requirements with regard to the release of components and vehicles.

A wide variety of test methods is used for testing interference immunity and interference emission. Depending on the methods used to assess interference phenomena, they can be roughly divided into methods operating in the time domain (pulse generators, oscilloscopes), and those operating in the frequency domain (sine-wave generators, test receivers, spectrum analyzers).

In measuring technology, interference signals are specified as relative quantities of interference emission in dB (decibels). The values for interference suppression (pulse amplitude, transmitter field strengths) are typically specified directly (Table 1).

Table 1: Measured values

Physical quantity	Reference variable	Unit	Calculations
Interference emission			
Voltage L_U	1 μV	dB (μV)	$L_U = 20 \lg (U/1 \mu\text{V})$
Current L_I	1 μA	dB (μA)	$L_I = 20 \lg (I/1 \mu\text{A})$
Field strength L_E	1 $\mu\text{V/m}$	dB ($\mu\text{V/m}$)	$L_E = 20 \lg (E/1 \mu\text{V/m})$
Power L_P	1 mW	dB (mW)	$L_P = 10 \lg (P/1 \text{ mW})$
Interference immunity			
Voltage U	–	V	–
Current I	–	A	–
Field strength E	–	V/m	–
Field strength H	–	A/m	–
Power P	–	W	–

EMC test methods

EMC test methods are described in relevant standards and divided into methods for the entire vehicle, for the components and systems (e.g. control units, sensors and actuators) and for integrated circuits (IC) and modules.

IC test methods

During the metrological assessment of integrated circuits (IC), the methods used are designed such that only the component itself is assessed instead of the combination of components with a peripheral circuit and larger conductor structures. The goal is to find out more about the EMC performance of an IC, independent of its various applications, e.g. in order to compare different ICs of the same type. The standardized test methods for this are divided into conducted and irradiated test methods for interference emission (IEC 61967, see Table 3), interference immunity with respect to electromagnetic fields (IEC 62132, see Table 3) and test methods for sending and influencing pulses (IEC 62215, see Table 3) and ESD (electrostatic discharges). Figure 6 shows

an example of a test circuit measuring conducted disturbances on individual IC pins.

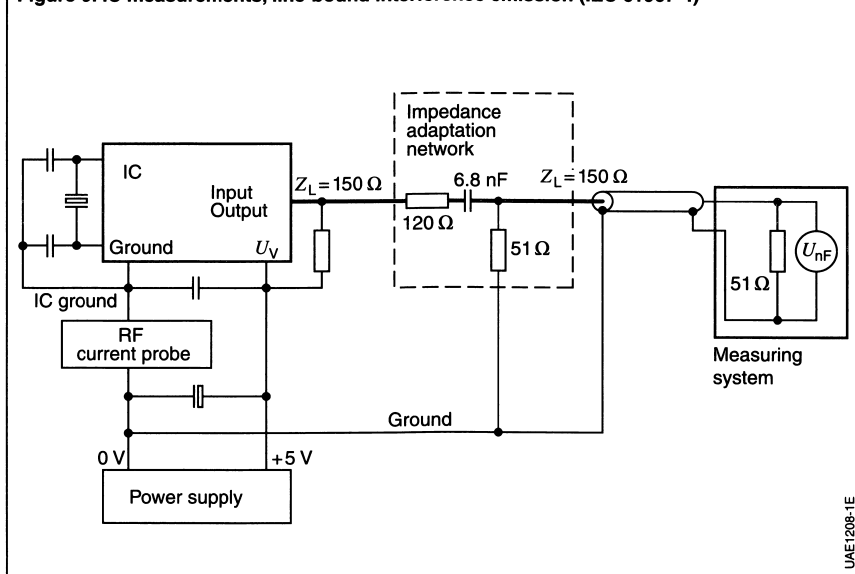
Component measurement methods

In assessing the devices in the laboratory, conducted test methods involving radiation are used. Test objects are always operated under standardized conditions. The power is supplied via vehicle line impedance stabilization networks (LISN), which simulate a uniform wiring harness. The measurement configuration is typically completed on a laboratory table with a ground plane. The test object is connected to measurement peripherals, which simulate its functioning in a realistic manner. In order to ensure isolation from its surroundings, the test setup is run in a shielded room.

Conducted disturbances

High-frequency interference voltages at the supply lines are capacitively decoupled in the Line Impedance Stabilisation Network, and interference currents are measured using suitable current measurement coils (CISPR 25, see Table 2).

Figure 6: IC measurements, line-bound interference emission (IEC 61967-4)



Immunity to pulsed interference is tested using special pulse generators which produce standardized test impulses in accordance with ISO 7637-2, Table 2. The coupling of pulsed interference on signal and control lines is reproduced using capacitive coupling clamps in accordance with ISO 7637-3. As with high-frequency interference emission measurements, the interference emission of pulses is measured in a standardized test setup through the use of relevant switches and oscilloscopes.

High-frequency interference coupling and interference emission

Interference immunity test

Coupling of electromagnetic waves for component measurements is achieved through the use of TEM waveguides like the stripline and the TEM cell (TEM, transverse electromagnetic mode) or the power coupling procedure BCI (Bulk Current Injection) and irradiation with antennas.

The principal measurement configuration always consists of a coupler for high frequencies in a shielded measuring room, a test object with a wiring harness, measurement peripherals, and devices

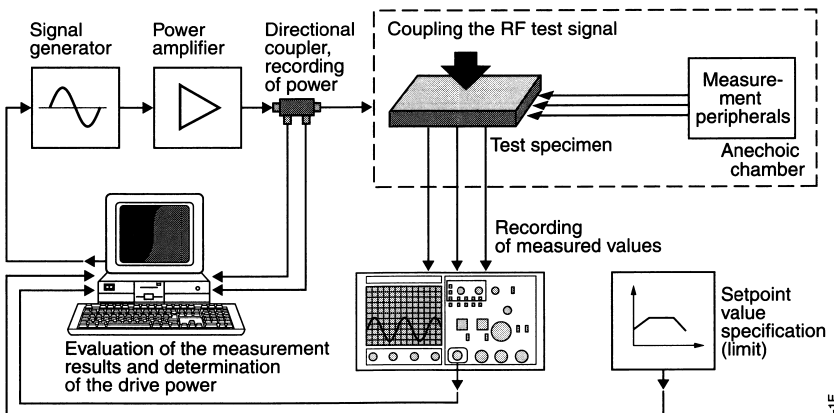
that produce high frequencies and recording and processing measured values (Figure 7).

In the case of a stripline, (ISO 11452-5, Table 2) the wiring harness is arranged in line with the direction of propagation of the electromagnetic wave between a strip conductor and a base plate. When a TEM cell is used (ISO 11452-3), the test object and a section of the wiring harness are arranged at a right angle to the propagation direction of the electromagnetic waves. The BCI method (ISO 11452-4) involves superimposing an RF current (radio frequency) on the wiring harness by means of a current clamp.

When the test setup is irradiated, the transmitting antennas are set up at various locations. Through this process, both the coupling of electromagnetic fields in the wiring harness and the coupling in the test object are reproduced.

These and further test methods, such as one for testing low-frequency magnetic fields (ISO 11452-8) and test methods for reproducing the interference coupling of mobile transmitters within close range (ISO 11452-9), are described in various portions of the ISO 11452 (Table 2).

Figure 7: Basic design of interference immunity tests



Measuring interference emission

The measuring principles for the immunity test can essentially be used to measure interference emission as well (CISPR 25). The TEM waveguides, current clamps and antennas function as receiving elements for the interference emitted by the test objects. For measuring the interference, the test receivers are connected directly to the receiving measuring instruments (Figure 8).

To decouple from the environment – that is, to ensure that only the interference produced by the test specimen is actually measured during interference emission measurements – and to minimize the emission of high-frequency signals in the environment when interference immunity tests are in progress, the testing for high-frequency disturbance values is carried out in electromagnetically shielded rooms. In order to avoid reflections and room resonance, shielded rooms are lined with high frequency absorbers when radiated signals are used.

Test methods**for electrostatic discharges**

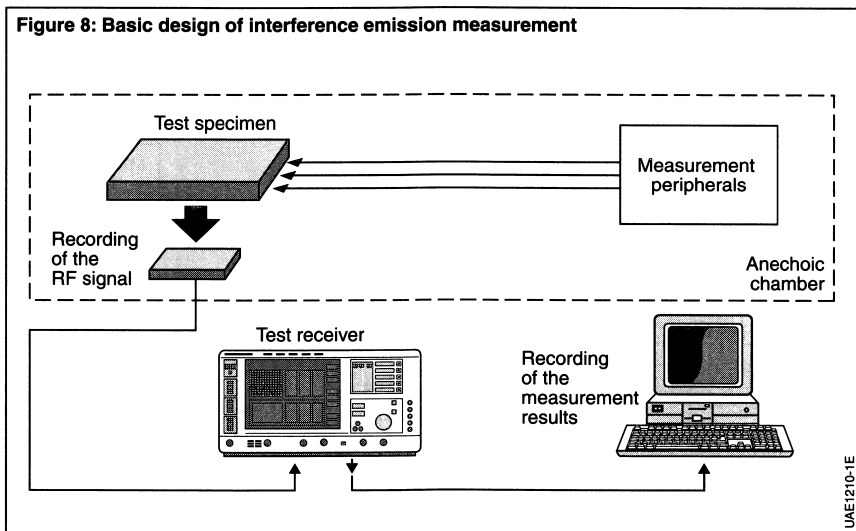
When assessing the interference immunity of ESD, special high voltage impulse generators are used. In these generators, the ESD impulse is reproduced by charging a smoothing capacitor and a targeted discharge via a discharge resistor. The capacity of the smoothing capacitor and the discharge resistor determine the energy output and the pulse shape. With a suitable discharge probe, the ESD pulse is applied to the coupling point, for example a control unit pin, either by a targeted rollover or after contact via a discharge switch in the alternator.

Vehicle testing procedures*Measuring interference immunity*

The immunity of electronic systems to electromagnetic fields radiated by high-power transmitters is tested on vehicle level in a special anechoic chambers (Figure 9). Here, high electrical and magnetic field strengths can be generated, and the whole vehicle can be exposed to them (ISO 11451, Table 2).

An interference emission of the entire vehicle is carried out with external antennas, either in standardized open area test sites or in anechoic chambers

Figure 8: Basic design of interference emission measurement



(IEC/CISPR 12, Table 2). The interference effects of the vehicle electrics and electronics on radio reception in the vehicle are measured using highly sensitive test receivers or spectrum analyzers. As far as possible, the original vehicle antenna is left in place, and measurements are taken at the receiver input terminal inside the vehicle in order to collect accurate data. With the help of a suitable test circuit, the impedance of the test receiver is adjusted to the input impedance of the receiver unit. The necessary limit values and measurement parameters like bandwidth and high frequency detectors are derived from the operating parameters of the radio services (IEC/CISPR 25).

Selection of EMC tests

The EMC tests carried out on an electric or electronic device depend on the component's area of application and its internal design. Simple electromechanical devices, which do not contain electronic components, do not have to be tested for interference immunity to electromagnetic fields. On the other hand, a variety of individual tests must be specified and implemented in EMC test plans for components containing electronic parts.

EMC simulation

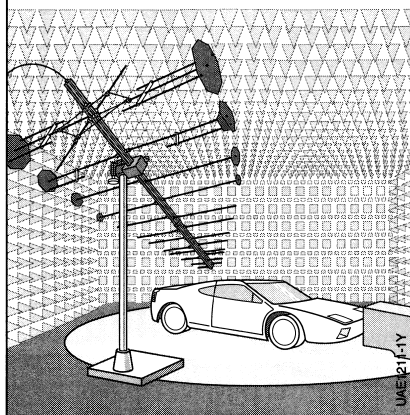
Nowadays, the application of numerical calculation methods is a method for the EMC development process equivalent to EMC measuring technology. Different calculation methods are employed depending on the problem at hand. What is critical in each case is accurate modeling of the sources of interference, potentially susceptible devices and the coupling path.

If the conducted coupling is dominant or the design of the electrical circuit (for example, filter structures) is to be examined, circuit simulation programs are usually used. If the field-coupled influence is dominant or geometric configurations (such as a metallic structure for shielding the electromagnetic fields or antenna geometry) are to be examined, various methods are used to calculate electromagnetic fields.

Thus the user has to select the method to be used depending on the problem to be solved. The EMC simulation can be used both when developing and assessing individual components, for designing components and systems, and for examining the entire vehicle, for example, to determine the optimum location for an antenna.

A significant advantage of the EMC simulation is that a wide variety of variants (for example, using different components or various geometric configurations) can be examined and compared without having to build and measure a design model for each one.

Figure 9: Interference immunity measurement in an EMC anechoic chamber for vehicles



Legal requirements and standards

EMC type approval

The form of electromagnetic compatibility for motor vehicles is prescribed by law such that, in addition to other requirements (for example, for brakes, light, exhaust gas), requirements concerning interference immunity to electromagnetic fields and regarding the maximum permissible interference emission (interference suppression) also have to be fulfilled for the type approval of vehicles. The currently applicable directive UNECE R10, Revision 5 from 2014 [1] is based on a directive from 1972, which merely contained requirements regarding interference suppression for the vehicle. Since then, this directive has been repeatedly adapted and supplemented to account for technical progress.

The current edition takes into account not only the requirements for conventional motor vehicles, but also requirements for electric and hybrid vehicles with built-in charging devices. Since these vehicles come into contact with the public power grid, there must be assurance of appropriate interference immunity to line-bound interference from the power grid and a corresponding limit to the interference from the vehicle into the power grid.

Two different paths can be taken for the type approval of vehicles. Usually, vehicle manufacturers apply for type approval via type test for the entire vehicle. However, it is also possible to obtain a type approval for electrical and electronic submodules. In this case, in addition to the limit values for interference immunity to electromagnetic fields and the interference radiation, requirements regarding the pulsed interference in the vehicle electrical system also have to be fulfilled.

In addition to regulations governing the type approval procedure for vehicles or components, UNECE R10 also specifies test methods and maximum limits. The test methods are based on the applicable international standards (Table 2); the limit values and precise execution are explicitly specified in the directive.

The defined limit values represent minimum requirements. In practice, just barely complying with the limit values specified is frequently insufficient to ensure interference-free reception or mobile communication in the vehicle. Depending on their vehicle concepts, therefore, the motor vehicle manufacturers specify in their own customer specifications both a raised requirement for interference immunity and a lower interference emission level for protecting radio reception. For the development of electric and electronic components, therefore, these requirements have to be taken into account from the start by consultation between the vehicle manufacturers and suppliers of vehicle electrical systems.

Standards

The individual, different test methods are described in the international ISO and IEC/CISPR standards according to Table 2 for vehicles and their electric/electronic components and systems. The IEC standards according to Table 3 treat the measuring methods for integrated circuits and semiconductor components. Usually the standards do not specify fixed limit values, but limit value classes. Depending on the individual vehicle concepts, this should enable the users of the standards (vehicle manufacturers and suppliers) to provide optimum technical and economical coordination between the requirements regarding interference immunity and interference emission.

Table 2: International standards for motor vehicles and components**Interference immunity**

Designation	Title
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Road vehicles – Electrical disturbances from conduction and coupling

ISO 7637-1	Part 1: Definitions and general considerations
ISO 7637-2	Part 2: Electrical transient conduction along supply lines only
ISO 7637-3	Part 3: Vehicles with nominal 12 V or 24 V supply voltage – Electrical transient transmission by capacitive and inductive coupling via lines other than supply lines
ISO/TR 7673-5	Part 5: Enhanced definitions and verification methods for harmonization of pulse generators according to ISO 7637

Road vehicles – Vehicle test methods for electrical disturbances from narrowband radiated electromagnetic energy

ISO 11451-1	Part 1: General principles and terminology
ISO 11451-2	Part 2: Off-vehicle radiation sources
ISO 11451-3	Part 3: Onboard transmitter simulation
ISO 11451-4	Part 4: Bulk current injection (BCI)

Road vehicles – Component test methods for electrical disturbances from narrowband radiated electromagnetic energy

ISO 11452-1	Part 1: General principles and terminology
ISO 11452-2	Part 2: Absorber-lined shielded enclosure
ISO 11452-3	Part 3: Transverse electromagnetic mode (TEM) cell
ISO 11452-4	Part 4: Bulk current injection (BCI)
ISO 11452-5	Part 5: Stripline
ISO 11452-7	Part 7: Direct radio frequency (RF) power injection
ISO 11452-8	Part 8: Immunity to magnetic fields
ISO 11452-9	Part 9: Portable transmitters
ISO 11452-10	Part 10: Immunity to conducted disturbances in the extended audio frequency range
ISO 11452-11	Part 11: Reverberation chamber

ESD – Electrostatic discharge

ISO 10605	Road vehicles – Test methods for electrical disturbances from electrostatic discharge
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Interference emission

Designation	Title
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Vehicles, boats and internal combustion engines

IEC/CISPR 12	Radio disturbance characteristics – Limits and methods of measurement for the protection of off-board receivers
IEC/CISPR 25	Limits and methods of measurement for the protection of on-board receivers

Table 3: International standards for semiconductor components (IC)

Pulses

Designation	Title
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Integrated circuits – Measurement of impulse immunity

IEC/TS 62215-2	Part 2: Synchronous transient injection method
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IEC 62215-3	Part 3: Non-synchronous transient injection method
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Interference immunity

Designation	Title
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Integrated circuits – Measurement of electromagnetic immunity

IEC 62132-1	150 kHz to 1 GHz – Part 1: General conditions and definitions
-------------	---

IEC 62132-2	Part 2: Measurement of radiated immunity – TEM cell and wideband TEM cell method
-------------	--

IEC 62132-3	150 kHz to 1 GHz – Part 3: Bulk current injection (BCI) method
-------------	--

IEC 62132-4	150 kHz to 1 GHz – Part 4: Direct RF power injection method
-------------	---

IEC 62132-5	150 kHz to 1 GHz – Part 5: Workbench Faraday cage method
-------------	--

IEC 62132-6	150 kHz to 1 GHz – Part 6: Local injection horn antenna (LIHA) method
-------------	---

IEC 62132-8	Part 8: Measurement of radiated immunity – IC stripline method
-------------	--

IEC/TS 62132-9	Part 9: Measurement of radiated immunity – Surface scan method
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Interference emission

Designation	Title
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Integrated circuits – Measurement of electromagnetic emissions

IEC 61967-1	150 kHz to 1 GHz – Part 1: General conditions and definitions
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IEC/TR 61967-1-1	Part 1: General conditions and definitions – Near-field scan data exchange format
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IEC 61967-2	150 kHz to 1 GHz – Part 2: Measurement of radiated emissions – TEM cell and wideband TEM cell method
-------------	--

IEC/TS 61967-3	150 kHz to 1 GHz – Part 3: Measurement of radiated emissions – Surface scan method
----------------	--

IEC 61967-4	150 kHz to 1 GHz – Part 4: Measurement of conducted emissions; 1 Ohm/150 Ohm direct coupling method
-------------	---

IEC/TR 61967-4-1	150 kHz to 1 GHz – Part 4-1: Measurement of conducted emissions – 1 Ohm/150 Ohm direct coupling method – Application guidance to IEC 61967-4
------------------	--

IEC 61967-5	150 kHz to 1 GHz – Part 5: Measurement of conducted emissions; Workbench Faraday cage method
-------------	--

IEC 61967-6	150 kHz to 1 GHz – Part 6: Measurement of conducted emissions – Magnetic probe method
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IEC 61967-8	Part 8: Measurement of radiated emissions – IC stripline method
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Additional references

[1] UNECE R10, Revision 5: Uniform provisions concerning the approval of vehicles with regard to electromagnetic compatibility

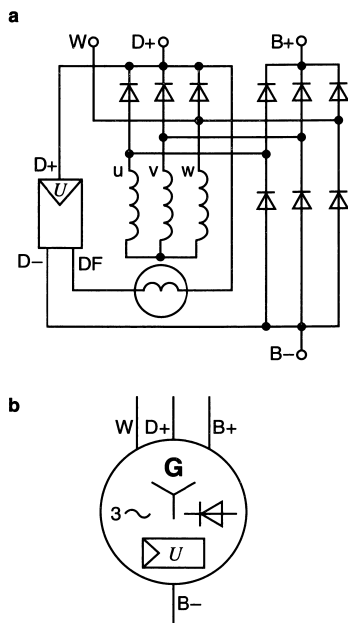
Symbols and circuit diagrams

The electrical systems in motor vehicles contain a large number of electric and electronic devices for controlling and managing the engine, and for safety and comfort and convenience systems. An overview of the complex vehicle electrical system circuits is only possible with meaningful symbols and circuit diagrams. Circuit diagrams such as schematic diagrams and terminal diagrams help in troubleshooting, simplify the installation of additional devices, and facilitate fault-free connection when retrofitting or altering the electrical equipment in motor vehicles.

Figure 1: Circuit diagram and circuit symbol of an alternator with regulator

The circuit symbols contains, in addition to the symbol for the alternator/generator G, the symbols for the three windings (phases), the star connection, the diodes, and the regulator.

- a) With internal circuitry,
b) Circuit symbol.



Circuit symbols

Standards

The circuit symbols shown in Table 1 are a selection of standardized circuit symbols which are suitable for automotive electrics. But for a few exceptions, they correspond to the standards of the International Electrotechnical Commission (IEC).

The European Standard EN 60617 (Graphical symbols for diagrams, [1]) corresponds to the International Standard IEC 60617. It exists in three official versions (German, English and French). The standard contains symbol elements, identifiers and above all circuit symbols for the following areas: General applications (Part 2), Conductors and connecting devices (Part 3), Basic passive components (Part 4), Semiconductors and electron tubes (Part 5), Production and conversion of electrical energy (Part 6), Switchgear, controlgear and protective devices (Part 7), Measuring instruments, lamps and signalling devices (Part 8), Telecommunications: Switching and peripheral equipment (Part 9), Telecommunications: Transmission (Part 10), Architectural and topographical installation plans and diagrams (Part 11), Binary logic elements (Part 12) and Analogue elements (Part 13).

Requirements

Circuit symbols are the smallest elements in a circuit diagram and the simplified graphical representation of an electrical device or a part thereof. The circuit symbols show the operating concept of a device and represent in circuit diagrams the functional correlations of a technical sequence. Circuit symbols do not take into consideration the shape and dimensions of the device and the position of the connections on the device. A detached representation in the schematic diagram is possible by abstraction only.

A circuit symbol should have the following properties: It should be easily remembered, easily comprehensible, uncomplicated in its graphic representation, and clearly within a classification group.

Circuit symbols consist of circuit-symbol elements and qualifying symbols. The following are examples of qualifying symbols: letters, numbers, symbols, mathematical signs and symbols, unit symbols, and characteristic curves.

If a circuit diagram becomes too elaborate due to the representation of the internal circuitry of a device (Figure 1a) or if not all the details of the circuit are needed to identify the function of the device, the circuit diagram for this special device can be replaced by a single circuit symbol (without internal circuitry) (Figure 1b).

In the case of integrated circuits which demonstrate a high degree of economy of space (this is synonymous with large scale integration of functions in a component), a simplified circuit representation is preferred.

Representation

The circuit symbols are shown without the effect of a physical quantity, i.e. in a de-energized and mechanically non-actuated state. An operating state of a circuit symbol that deviates from this standard representation (basic status) is denoted by an adjacent double arrow (Figure 2).

Circuit symbols and connecting lines (representing electric lines and mechanical linkages) have the same line width.

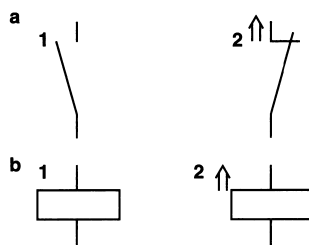
To avoid unnecessary kinks and crossings of the connecting lines, it is possible to rotate circuit symbols in 90° increments or show a mirror image of them, provided this does not alter their meaning. The direction of continuing lines can be freely selected. Exceptions are the circuit symbols for resistors (connection symbols are only permitted here on the narrow sides) and connections for electromechanical drives (connection symbols are only permitted here on the wide sides, Figure 3).

Junctions are represented both with and without a dot. Where there are crossings without a dot, there is no electrical connection. Connecting points on devices are for the most part not specifically represented. Connecting point, plug, jack or screwed connections are identified by a circuit symbols only at the points required for installation and removal. Other connecting points are identified as standard by dots.

Contact elements with a common drive are identified in an assembled representation in such a way that on actuation they follow a direction of motion which is established by the mechanical linkage (---) (Figure 4).

Figure 2: Operating state of the circuit symbol deviating from the basic status

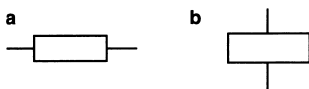
- a) NO contact,
b) Electromechanical drive.
1 Basic status,
2 Deviation.



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Figure 3: Terminals

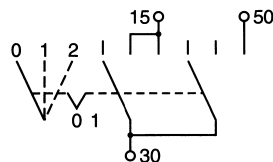
- a) Resistor,
b) Electromechanical drive.



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Figure 4: Mechanical linkage at a multi-position switch

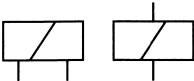
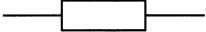
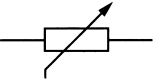
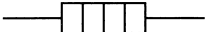
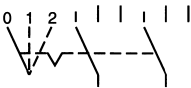
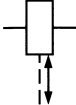
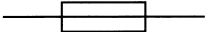
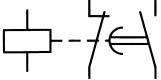
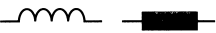
- 0, 1, 2 Switch positions,
15, 30, 50 Terminal designations.

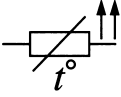
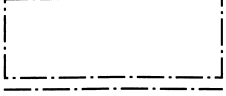
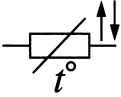
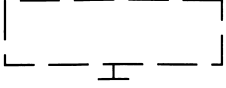
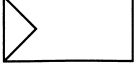
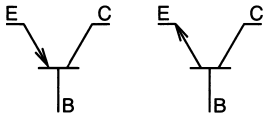
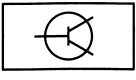
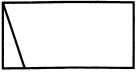
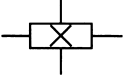


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Table 1: Selection of circuit symbols as per EN 60617

Connections	Mechanical function	
Line; line intersection, without/with a connection	Switch positions (home position: solid line)	Variability/adjustability, not intrinsic (external), general
Shielded line		Variability/adjustability, intrinsic, caused by applied physical variable, linear/non-linear
Mechanical linkage; electrical conductor (laid at later stage)		
Crossovers (without/with connections)	Activation is manual, by sensor (cam), thermal (bimetal)	Variability/adjustability, general
Connection, general; separable connection (if indication necessary)	Detent; non-automatic/automatic return in direction of arrow (button)	Switches
		Pushbutton switch, NO/NC contact
Plug connection; socket; plug; three-plug connection	Actuator, general (mech., pneum., hydraul.); piston actuation	
		Detent switch, NO/NC contact
Ground (housing ground, vehicle ground)	Actuation by rotational speed n , pressure p , quantity Q , time t , temp. t°	
		Changeover contact, non-bridging/bridging

Switches	Various components	
Two-way normally open contact with three positions (e.g. turn-signal indicator switch) 	Actuators with one winding 	Resistor 
NO/NC contact 	Actuator with two windings acting in same direction 	Potentiometer (with three connections) 
Contact with two makes 	Actuator with two windings acting in opposing directions 	Heating resistor, glow plug, flame plug, heated window 
Multiple-position switch 	Electrothermal actuator, thermal relay 	Antenna 
Cam-operated switch (e.g. contact breaker) 	Electrothermal actuator, linear solenoid 	Fuse 
Thermostatic switch 	Solenoid valve, closed 	Permanent magnets 
Release/trip device 	Relay (actuator and switch), example: non-delayed-break NC contact and delayed-break NO contact 	Winding, inductive 

Various components	Devices in motor vehicle	
PTC resistor 	Dotted/dashed line used to delineate or group together associated circuit sections 	Battery 
NTC resistor 	Shielded device, dashed line connected to ground 	Plug-and-socket connection 
Diode, general, current in direction of triangle tip 	Regulator, general 	Light, headlamp 
PNP transistor NPN transistor E = Emitter (arrow points in direction of flow) C = Collector, positive B = Base (horizontal), negative 	Electronic control units (ECUs)  	Horn, fanfare horn 
Light-emitting diode (LED) 	Indicating instrument, general; voltmeter; clock 	Heated rear window (general heating resistor) 
Hall generator 	Rotational-speed indicator; temperature indicator; linear-speed indicator 	Switch, general, without indicator lamp  Switch, general, with indicator lamp 

Devices in motor vehicle

Pressure switch



Relay, general



Solenoid valve, fuel injector, cold-start valve



Thermo-time switch



Throttle-valve switch



Rotary actuator



Auxiliary-air valve with electrothermal actuator



Spark plug



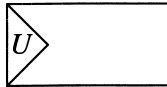
Ignition coil



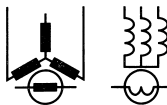
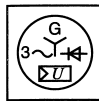
Ignition distributor, general



Voltage regulator



Alternator with regulator (without/with internal circuitry)



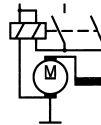
Electric fuel pump, engine drive for hydraulic pump



Motor with blower, fan



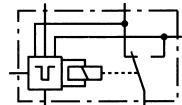
Starter motor with engagement relay (without/with internal circuitry)



Wiper motor (one/two wiper speeds)



Intermittent-wiper relay



Car radio



Devices in motor vehicle

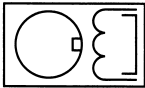
Loudspeaker



Voltage stabilizer, stabilizer



Inductive sensor, controlled with reference mark



Turn-signal flasher, pulse generator, intermittent relay



Lambda oxygen sensor (unheated/heated)



Piezoelectric sensor



Resistance sensor



Air-flow sensor



Air-mass meter



Flow-quantity sensor, fuel-level sensor



Temperature switch, temperature sensor



Linear-speed sensor



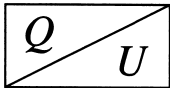
ABS rotational-speed sensor



Hall sensor



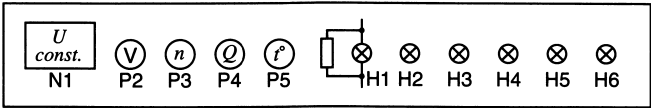
Converter (rate, voltage)



Inductive sensor



Instrument-cluster device (dashboard)



Circuit diagrams

Circuit diagrams are idealized representations of electrical devices, rendered in the form of symbols. Such diagrams also include illustrations and simplified design drawings as needed. A circuit diagram illustrates the relationship between the various devices and shows how they are connected to each other. A circuit diagram may be supplemented by tables, graphs, or descriptions. The type of circuit diagram actually used is determined by its particular purpose (e.g. illustrating the operation of a system), and by the way in which the circuit is represented (Figure 5).

For a circuit diagram to be “legible”, it must satisfy the following requirements:

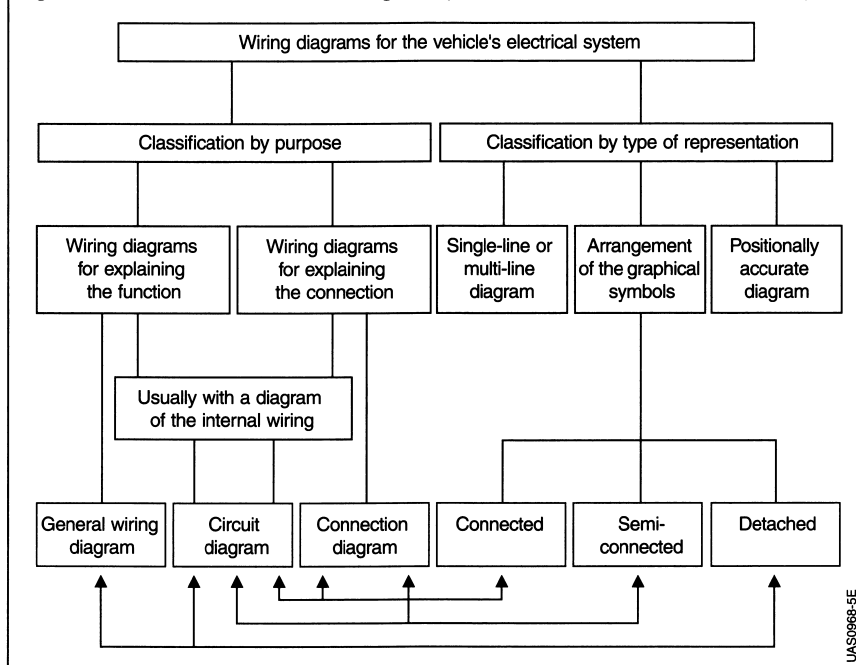
- It must comply with the requirements of the appropriate standards, and deviations must be explained.
- Current paths should be arranged so that current flow or mechanical action takes place from left to right or from top to bottom.

In automotive electrics, block diagrams with single inputs and outputs and with internal circuitry omitted provide a swift overview of the function of a system or a device. The schematic diagram in different methods of representation (layout of the circuit symbols) is the detailed representation of a circuit to identify the function and to carry out repairs. The terminal diagram (with terminal locations of the devices) is used by the Aftersales Service when replacing or retrofitting devices.

According to the method of representation, a distinction is made between

- single- or multi-line representation, and (according to the layout of the circuit symbols)
- assembled, semi-assembled, detached and topographical representation, which can be combined in one and the same circuit diagram.

Figure 5: Classification of the circuit diagrams (in accordance with EN 81346, Part 1 [2])



Block diagram

The block diagram is the simplified representation of a circuit, where only the essential parts are taken into consideration (Figure 6). It is intended to provide a quick overview of the task, design, structure and function of an electrical system or a part thereof, and to serve as a guide for more detailed circuit documentation (schematic diagram).

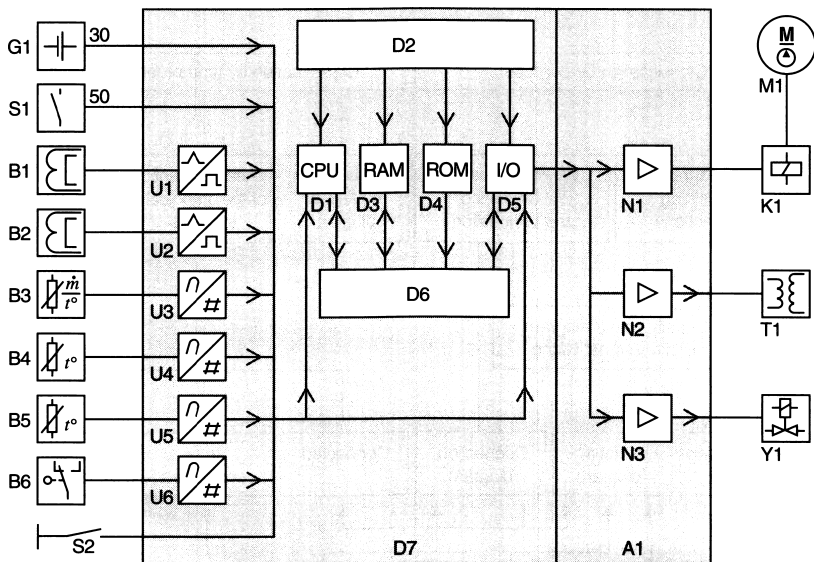
The devices are depicted by squares, rectangles and circles with qualifying symbols inside them similar to EN 60617, Part 2. The lines are for the most part drawn as single lines.

Schematic diagram

A schematic diagram is the detailed representation of a circuit. By clearly depicting individual current paths, it also indicates how an electrical circuit operates. In a schematic diagram, the clear presentation of the circuit's operation, which makes the diagram easy to read, must not be interfered with by the presentation of the individual circuit components and their spatial relationships. Figure 7 shows the schematic diagram of a starter motor in assembled and detached representations.

Figure 6: Block diagram of a Motronic ECU as an example

A1 ECU,
B1 Sensor for engine speed, B2 Sensor for reference mark,
B3 Sensor for air mass, B4 Sensor for intake-air temperature,
B5 Sensor for engine temperature, B6 Throttle-valve switch,
D1 Computing unit (CPU), D2 Address bus, D3 Main memory (RAM),
D4 Program data memory (ROM), D5 Input – Output,
D6 Data bus, D7 Microcomputer,
G1 Battery, K1 Pump relay, M1 Electric fuel pump,
N1 to N3 Driver stages,
S1 Ignition/starter switch, S2 Map changeover switch,
T1 Ignition coil, U1, U2 Pulse shapers, U3 to U6 Analog-digital converters,
Y1 Fuel injector.



The schematic diagram must contain:

- circuit,
- device identification (EN 81346, Part 2, [2]), and
- pin designation and terminal designation (DIN 72552, [3]).

The schematic diagram can contain:

- A complete representation with internal circuitry in order to facilitate testing, fault localization, maintenance and replacement (retrofitting).
- Reference designations to better locate circuit symbols and destinations, particularly in a detached representation.

Representation of the circuit

Mostly multi-line representation is used in the schematic diagram. For the layout of the circuit symbols, there are, in accordance with EN 81346 Part 1, the following methods of representation which can be combined in the same circuit diagram.

Assembled representation

All the parts of a device are directly represented together assembled and connected to each other by a double slash or discontinuous connecting lines to identify the mechanical linkage. This representation can be used for simple, not very com-

Figure 7: Schematic diagram of a KB-type starter motor for parallel operation using two methods of representation

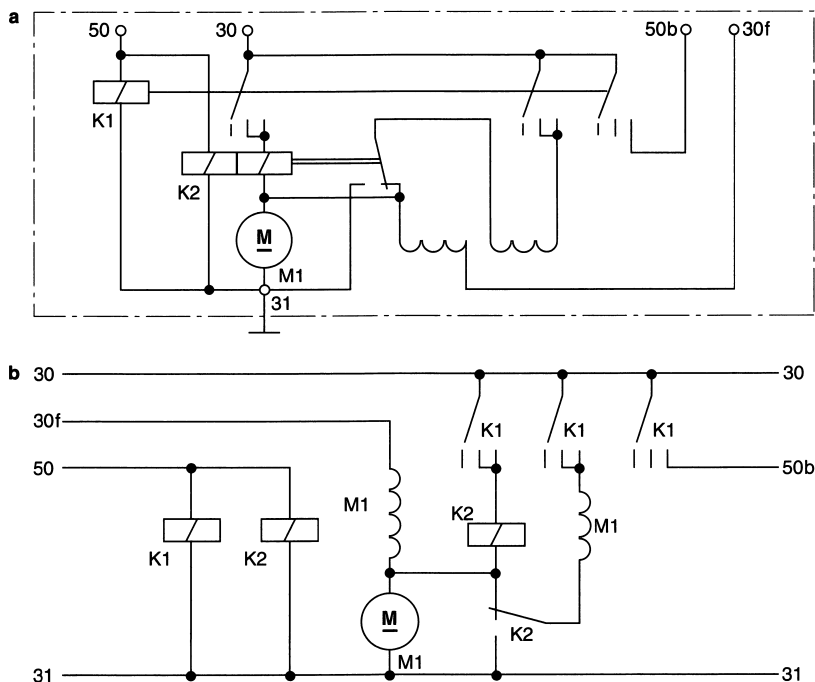
a) Assembled representation,

b) Detached representation.

K1 Control relay, K2 Engagement relay, holding winding and pull-in winding,

M1 Starter motor with series and shunt windings.

30, 30f, 31, 50b Terminal designations.



prehensive circuits without a loss of clarity (Figure 7a).

Detached representation

Circuit symbols of parts of electrical devices are represented separately and arranged in such a way that each current path can be traced as easily as possible (Figure 7b). The spatial association of individual devices or their parts is not taken into consideration. The priority is for the layout of the current paths to be as linear, clear and crossing-free as possible. The main purpose of this representation is to identify the function of a circuit.

The association of the individual parts must be identified using an identification system in accordance with EN 81346, Part 2. The identification associated with a device is located on each individual, separately represented circuit symbol for that device. Devices shown detached must be indicated once complete and assembled

at a point in the circuit diagram if this is necessary to understand the circuit.

Topographical representation

In this representation, the position of the circuit symbol entirely or partially corresponds to the spatial position within the device or part.

Ground representation

For most motor vehicles, the single-conductor system, in which ground (metal parts of the vehicle) acts as the return conductor, is preferred for its simplicity. If a perfectly conducting connection of the individual ground parts is not guaranteed or if voltages in excess of 42 V are involved, the return conductor is also laid insulated from ground.

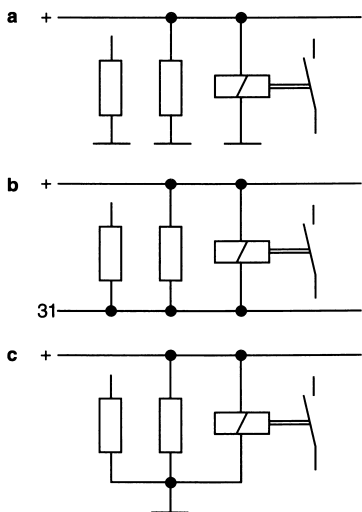
All the ground symbols represented in a circuit are electrically connected to each other via device or vehicle ground.

All the devices which contain a ground symbol must be connected to vehicle ground and be electrically conductive.

Figure 8 shows different possibilities of ground representation.

Figure 8: Ground representation

- a) Individual ground symbols,
 - b) Ground continuity,
 - c) With ground collecting point.
- 31 Terminal designation.



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Current paths and lines

The circuits are arranged in such a way as to produce and clear representation. The individual current paths, with the effective direction preferably from left to right or from top to bottom, should generally run parallel to the edge of the circuit diagram as linearly as possible, crossing-free and without changes of direction.

When there is a bundling of parallel lines, these are grouped into units of three lines each, and there follows a gap to the next group.

Boundary lines and framings

Dot-and-dash separating or framing lines delimit parts of circuits in order to show the functional or design association of the devices or parts.

In automotive electrical systems, this dot-and-dash line represents a non-conductive framing of devices or circuit parts; it does not always correspond to the circuit housing and is not used as device ground. In high-voltage electrical systems, this framing line is often connected to the protective earth conductor (PE),

which is also indicated by a dot-and-dash line.

Break points, identifier, destination designation

Connecting lines (lines and mechanical linkages) which run over a longer distance of the schematic diagram can be interrupted in order to improve clarity. Only the beginning and the end of the connecting line are represented. The association of these break points must be clearly identifiable. The identifier and the destination designation are used for this purpose (Figure 9).

The identifier at associated break points matches. Terminal designations in accordance with DIN 72552 (Figure 9a), the specification of the operating concept and specifications in the form of alphanumeric characters serve as the identifier.

The destination designation is enclosed in parentheses so that it is not confused with the identifier; it consists of the section number of the destination (Figure 9b).

Section designation

The section designation indicated at the top edge of the diagram (formerly called the current path) is used to locate circuit parts. This designation can take three different forms:

- consecutive numbers at the same intervals from left to right (Figure 10a),
- reference to the contents of the circuit sections (Figure 10b),
- or a combination of the two (Figure 10c).

Labeling

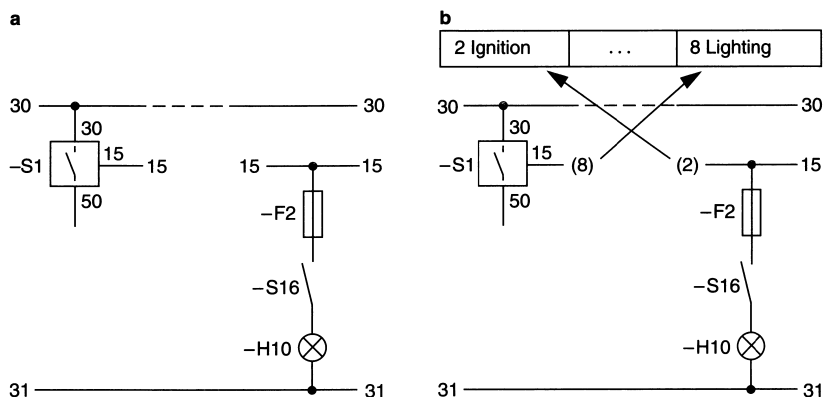
Devices, parts or circuit symbols are identified in circuit diagrams with a letter and a number in accordance with EN 81346, Part 2. This identification is placed on the left or underneath the circuit symbol.

The qualifying symbol specified in the standard for the type of devices can be omitted if this does not give rise to ambiguity.

In the case of nested devices, a device is a component part of another, e.g. starter M1 with built-in engagement relay K6. The device designation is then: – M1 – K6. Designation of associated circuit symbols in a detached representation: Each individual, separately represented circuit symbol of a device is given the designation common to the device.

Figure 9: Identification of break points

- a) By terminal designation, e.g. term. 15,
b) By destination designation, e.g. in section 8 and 2.



Pin designations (e.g. in accordance with DIN 72552) must be written outside the circuit symbol, and in the case of framing lines preferably outside the framing.

Where the current paths run horizontally: The specifications assigned to the individual circuit symbols are written under the relevant circuit symbols. The terminal designation is located directly outside the actual circuit symbols above the connecting line.

Where the current paths run vertically: The specifications assigned to the individual circuit symbols are written on the left

next to the relevant circuit symbols. The terminal designation is located directly outside the actual circuit symbol, on the right if the format is horizontal and on the left next to the connecting line if the format is vertical.

Terminal diagram

The terminal diagram shows the terminal locations of electrical devices and the connected outer and – if necessary – inner conductive connections (lines).

Representation

The individual devices are represented by squares, rectangles, circles and circuit symbols or even pictorially represented, and can be topographically arranged. Circle, dot, plug-in connection or only the led out line are used as terminal points.

The following methods of representation are customary in automotive electrics:

- Assembled, circuit symbols corresponding to EN 60617 (Figure 11a).
- Assembled, pictorial device representation (Figure 11b).
- Detached, device representation with circuit symbols, terminals with destination designations (Figure 12a); lines can be color coded.
- Detached, pictorial device representation, terminals with destination designations (Figure 12b); lines can be color coded.

Figure 10: Possible section designations

- With consecutive numbers,
- With references to the sections,
- With a combination of a and b.

a

1	2	3	4	5	6	7	8	...
---	---	---	---	---	---	---	---	-----

b

1 Power supply	2 Starting system	3 Ignition
----------------	-------------------	------------

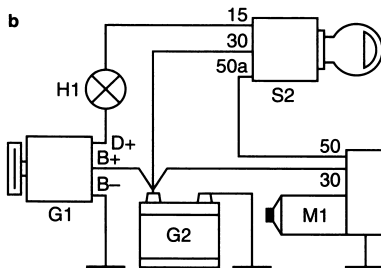
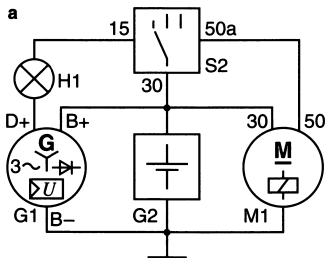
c

1	2	3	4	5	6	7	8	9	10
Power supply			Starting system			Ignition			

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Figure 11: Example of a terminal diagram (assembled representation)

- With circuit symbols,
- With devices.



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Labeling

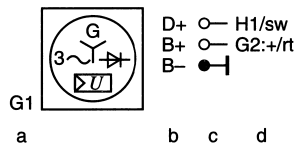
The devices are labeled in accordance with EN 81346, Part 2. Terminals and plug-in connections are identified with the terminal designations present on the device (Figure 11).

In the detached method of representation, the continuous connecting lines between the individual devices are omitted. All outgoing lines from a device are given a destination designation (EN 81346, Part 2), consisting of the identification of the destination device and its terminal designation, and – if necessary – the line color is also given (Figure 13).

Figure 13: Device designation (example: alternator)

- Device designation (code letter and code number),
- Terminal designation on device,
- Device to ground,
- Destination reference (code letter and code number/terminal designation/wire color).

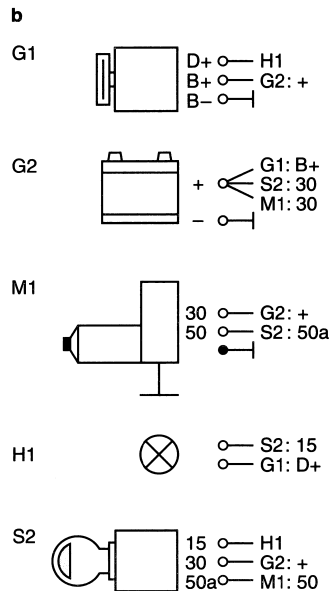
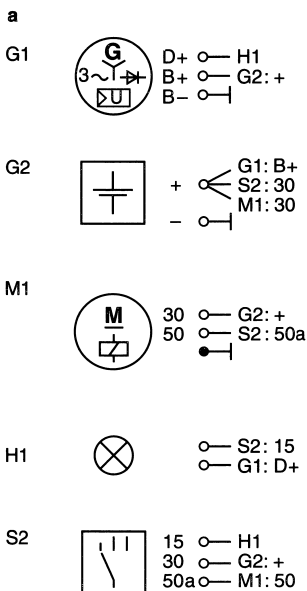
Device diagram Destination designation



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Figure 12: Terminal diagram (detached representation)

- With circuit symbols and destination designations,
 - With devices and destination designations.
- G1 Alternator with regulator, G2 Battery, H1 Alternator indicator lamp, M1 Starter motor, S2 Ignition/starter switch, 15, 30, 50, 50a Line potential, e.g. terminal 15.



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Assembled-representation diagram

For troubleshooting on complex and extensively networked systems with self-diagnosis function, Bosch has developed system-specific schematic diagrams. Bosch makes assembled-representation diagrams for further systems in a great number of motor vehicles available in ESI[tronic] (Bosch Electronic Service Information). This provides automotive repair shops with a useful tool for locating faults or wiring retrofit equipment. Figure 15 shows as an example the assembled-representation diagram for a door locking system.

In contrast to other schematic diagrams, the assembled-representation diagrams use US symbols that are supplemented by additional descriptions (Figure 14). These include component codes – e.g. “A28” (theft-deterrence system) –, which are explained in Table 2 and an explanation of the wire colors (Table 3). Both tables can be called up in ESI[tronic].

Table 2: Explanation of component codes

Position	Designation
A1865	Electrically adjustable seat system
A28	Theft-deterrence system
A750	Fuse box, relay box
F53	Fuse C
F70	Fuse A
M334	Supply pump
S1178	Warning-buzzer switch
Y157	Vacuum actuator
Y360	Actuator, door, front, right
Y361	Actuator, door, front, left
Y364	Actuator, door, rear, right
Y365	Actuator, door, rear, left
Y366	Actuator, filler cap
Y367	Actuator, lock, luggage compartment, trunk lid, tailgate

Table 3: Explanation of wire colors

Position	Designation
BLK	Black
BLU	Blue
BRN	Brown
CLR	Clear
DK BLU	Dark blue
DK GRN	Dark green
GRN	Green
GRY	Gray
LT BLU	Light blue
LT GRN	Light green
NCA	Color not known
ORG	Orange
PNK	Pink
PPL	Purple
RED	Red
TAN	Tan
VIO	Violet
WHT	White
YEL	Yellow

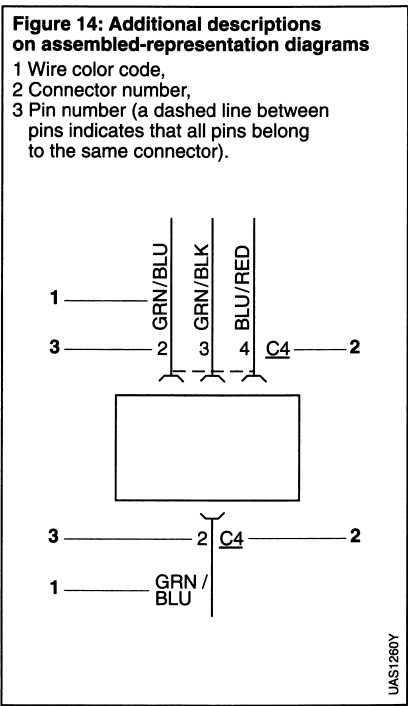
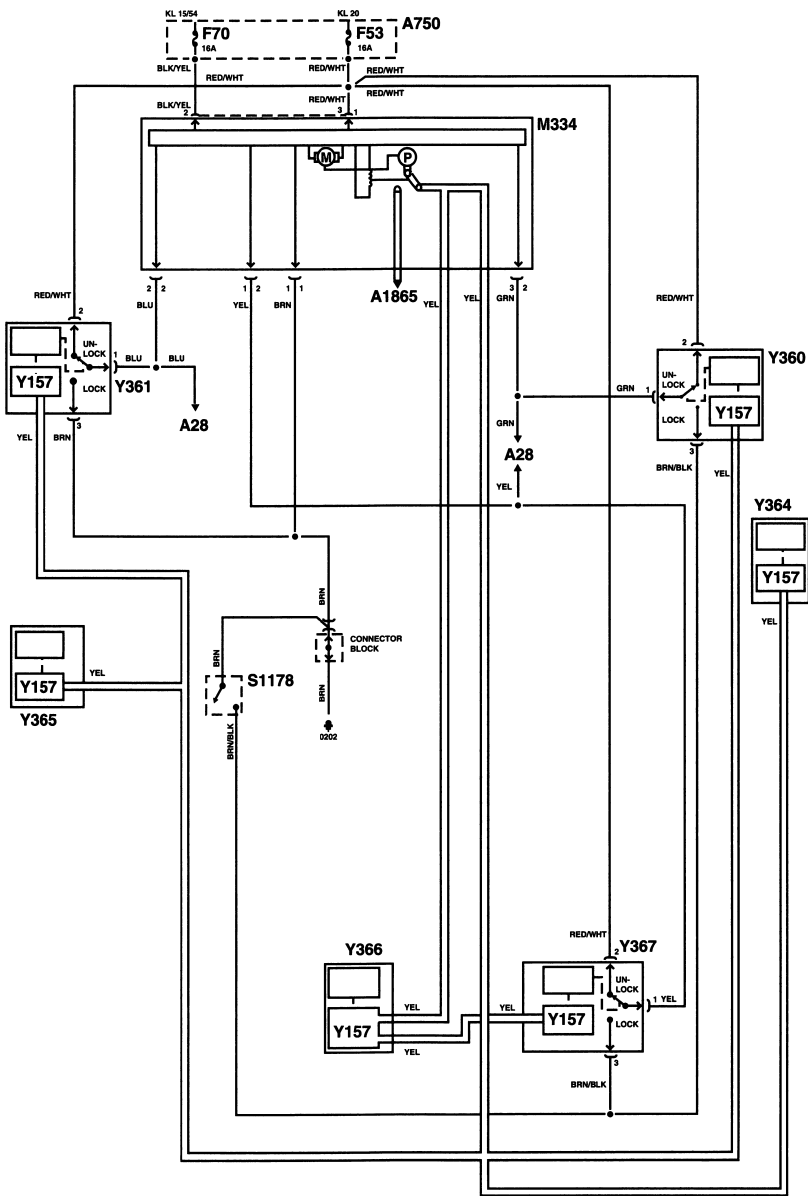


Figure 15: Assembled-representation diagram of a door locking system (example)



The assembled-representation diagrams are subdivided into system circuits and, if applicable, subsystems (see Table 4). Classification of system circuits reflects the standard ESI[tronic] practice as used for other systems, according to which they are assigned to one of four assembly groups:

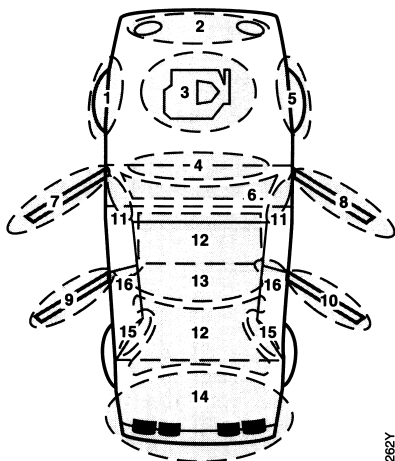
- engine,
- body,
- chassis/suspension,
- drivetrain.

Table 4: System circuits

1	Engine management
2	Starting/charging
3	Air conditioner/heating (HVAC)
4	Radiator blower
5	ABS
6	Cruise control
7	Power-window units
8	Central locking system
9	Dashboard
10	Washer/wiper system
11	Headlamps
12	Exterior lights
13	Power supply
14	Grounding
15	Data line
16	Shift lock
17	Theft deterrence
18	Passive safety systems
19	Power antenna
20	Warning system
21	Heated windshield/mirrors
22	Supplementary safety systems
23	Interior lights
24	Power steering
25	Mirror adjuster
26	Soft-top controls
27	Horn
28	Trunk, tailgate
29	Seat adjustment
30	Electronic damping
31	Cigarette lighter, socket
32	Navigation
33	Transmission
34	Active body components
35	Vibration damping
36	Cellular phone
37	Automotive sound system, Hi-Fi
38	Immobilizer

Figure 16: Grounding points

- 1 Left front fender,
- 2 Front end,
- 3 Engine,
- 4 Bulkhead,
- 5 Right front fender,
- 6 Footwell bulkhead/dashboard,
- 7 Left front door,
- 8 Right front door,
- 9 Left rear door,
- 10 Right rear door,
- 11 A pillars,
- 12 Passenger compartment,
- 13 Roof,
- 14 Rear end,
- 15 C pillars,
- 16 B pillars.



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It is important to be aware of the grounding points, particularly when fitting additional accessories. For this reason, ESI[tronic] includes the vehicle-specific location diagram for the grounding points (Figure 16) in addition to the assembled-representation diagrams.

Designations for electrical devices

The designations in accordance with EN 81346 Part 2 (Table 5) are used to provide a clear, internationally comprehensible identification of systems, parts, etc. which are represented by circuit symbols in a circuit diagram. They appear next to the circuit symbols and consist of a series of defined qualifying symbols, letters and numbers (Figure 17).

Figure 17: Device designation

Example: Alternator G2, terminal 15.

Designation as per standard:
qualifying symbol (can be omitted if there is no ambiguity)

Code letter for type
(here: alternator) from Table 5

Code number

Terminal (here: terminal 15)
as standardized designation or
designation marked on the device

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Table 5: Code letters for designating electrical devices as per EN 81346-2

Code letter	Type	Examples
A	System, assembly, component group	ABS ECU, automotive sound system, car radiotelephone, car phone, theft-deterrence system, device assembly, control device, ECU, cruise control
B	Converter of non-electrical into electrical quantities or vice versa	Reference-mark transmitter, pressure switch, fanfare horn, horn, λ oxygen sensor, loudspeaker, air-flow sensor, microphone, oil-pressure switch, sensors of all types, ignition trigger
C	Capacitor	Capacitors of all types
D	Binary element, memory	On-board computer, digital equipment, integrated circuit, pulse counter, magnetic tape recorder
E	Assorted devices and equipment	Heater, air-conditioning system, lamp, headlamp, spark plug, ignition distributor
F	Protective device	Trigger (bimetal), polarity protection device, fuse, current protection circuit
G	Power supply, alternator	Battery, alternator, charger
H	Check device, signaling unit, signaling device	Acoustic signaling unit, function lamp, turn-signal indicator, turn-signal lamp, brake-pad indicator, stop lamp, high-beam indicator, alternator charge indicator, indicator lamp, signaling unit, oil-pressure indicator, optical signaling unit, signal lamp, warning buzzer
K	Relay, contactor	Battery relay, turn-signal flasher, turn-signal relay, engagement relay, starting relay, hazard warning light flasher
L	Inductance	Inductance coil, coil, winding
M	Engine type	Blower motor, fan motor, pump motor for ABS, TCS and ESC hydraulic modulators, windshield-washer and windshield-wiper motors, starter motor, servomotor
N	Regulator, amplifier	Regulator (electronic or electromechanical), voltage stabilizer

Table 5: Code letters for designating electrical devices (continued)

Code letter	Type	Examples
P	Tester	Ammeter, diagnostic socket, rev counter, pressure indication, tachograph, measuring point, check point, speedometer
R	Resistance	Sheathed-element glow plug, flame glow plug, heating resistor, NTC resistor, PTC resistor, potentiometer, regulating resistor, series resistor
S	Switch	Switches and buttons of all types, ignition contact breaker
T	Transformer	Ignition coil, ignition transformer
U	Modulator, converter	DC converter
V	Semiconductor, tube	Darlington, diode, electron tube, rectifier, semiconductors of all types, variable capacitance diode, transistor, thyristor, Zener diode
W	Transmission path, line, antenna	Vehicle antenna, shield part, shielded line, lines of all types, line bundle, ground (continuity) line
X	Terminal, plug, plug-in connection	Terminal stud, electrical terminals of all kinds, spark-plug connector, terminal, terminal strip, electrical cable coupler, line connector, plug, socket, plug connector, (multiple) plug-in connection, distributor connector
Y	Electrically actuated mechanical equipment	Permanent magnet, (solenoid) fuel injector, electromagnetic clutch, electromagnetic brake, electric air slider, electric fuel pump, electromagnet, electric starting valve, transmission control, linear solenoid, kickdown solenoid valve, headlight leveling control, level control valve, switching valve, starting valve, door locking, central locking system, auxiliary-air slider
Z	Electric filter	Screening unit, suppression filter, filter chain, timer

Terminal designations

The purpose of the terminal-designation system for automotive electrical systems specified by the standard (DIN 72552) is to enable the most accurate connection of wires to all the various devices, above all when making repairs and installing spare parts. The terminal designations (Table 6) do not identify the wires because devices with different terminal designations can be connected at the two ends of each wire.

For this reason, they need not be written on the wires.

In addition to the terminal designations listed, designations according to DIN VDE standards may also be used on electrical machines. Multiple connectors, for which the number of terminal designations as per DIN 72552 no longer suffice, are numbered by consecutive numbers or letters whose function assignment is not specified by standards.

Table 6: Terminal designations according to DIN 72552

Terminal	Definition	Terminal	Definition
	Ignition coil		Starter
1	Low voltage	45	Separate starter-motor relay, output; starter, input (primary current)
4	High voltage		Dual starters, parallel activation
4a	From ignition coil I, terminal 4		Starting relay for pinion-engagement current
4b	From ignition coil II, terminal 4	45a	Starter I output, Starter I and II input
15	Switched positive after battery (ignition-switch output)	45b	Starter II output
15a	Output at the series resistor to the ignition coil and to the starter	48	Terminal on starter and start repeating relay (monitoring the starting process)
	Preheating system		Hazard-warning and turn-signal flashers
17	Start	49	Input, turn-signal flasher
19	Preglow	49a	Output, turn-signal flasher
	Battery	49b	Output, second turn-signal flasher
30	Line from battery positive terminal (direct)	49c	Output, third turn-signal flasher
30a	Battery changeover 12/24 V		Starter
	Line from battery II positive terminal	50	Starter control (direct)
31	Return wire from battery		Battery changeover relay
	Negative or ground (direct)	50a	Output for starter control
	Return wire to battery		Starter control
	Negative or ground via switch	50b	In parallel operation of two starter motors with sequence control
31 b	or relay (switched negative)		Starting relay for sequence control
	Battery changeover relay 12/24 V		of engagement current in parallel operation of two starter motors
31a	Return line to battery II negative	50c	Input at starting relay for starter I
31c	Return line to battery I negative	50d	Input at starting relay for starter II
	Electric motors		Start-locking relay
32	Return line ¹⁾	50e	Input
33	Main terminal ¹⁾	50f	Output
33a	Self-parking		Start repeating relay
33b	Shunt field	50g	Input
33f	for second reduced-rpm operation	50h	Output
33g	for third reduced-rpm operation		
33h	for fourth reduced-rpm operation		
33L	Rotation to left (counterclockwise)		
33R	Rotation to right (clockwise)		

¹⁾ Polarity reversal terminal 32/33 possible

Table 6: Terminal designations according to DIN 72552 (continued)

Terminal	Definition	Terminal	Definition
	Wiper motors		Current relay
53	Wiper motor, input (+)	84	Input, output, relay contact
53a	Wiper (+), self-parking	84a	Output, drive
53b	Wiper (shunt winding)	84b	Output, relay contact
53c	Electric windshield-washer pump		Switching relay
53e	Wiper (brake winding)	85	Output, drive
53i	Wiper motor with permanent magnet and third brush for higher speed)		(end of winding negative or ground)
	Lighting	86	Input, drive (start of winding)
55	Fog lamps	86a	Start of winding / 1st winding
56	Headlamps	86b	Winding tap / 2nd winding
56a	High beam with indicator lamp		Relay contact for NC contact and changeover contact:
56b	Low beam (dipped beam)	87	Input
56d	Headlamp-flasher contact	87a	1st output (NC side)
57a	Parking lamp	87b	2nd output
57L	Parking lamp, left	87c	3rd output
57R	Parking lamp, right	87z	1st input
58	Side-marker, tail, license-plate and instrument lamps	87y	2nd input
58L	left	87x	3rd input
58R	right		Relay contact for NO contact:
	Alternators and voltage regulators	88	Input
61	Alternator charge indicator		Relay contact for NO contact and changeover contact (NO contact side):
B+	Battery positive terminal	88a	1st output
B-	Battery negative terminal	88b	2nd output
D+	Alternator positive terminal	88c	3rd output
D-	Alternator negative terminal		Relay contact for NO contact:
DF	Alternator field winding	88z	1st input
DF1	Alternator field winding 1	88y	2nd input
DF2	Alternator field winding 2	88x	3rd input
U, V, W	Three-phase terminals		Turn-signal lamp (turn-signal flasher)
	Audio systems	C	1st indicator light
75	Radio, cigarette lighter	C0	Main terminal for check circuits separate from flasher
76	Loudspeaker	C2	2nd indicator lamp
	Switches	C3	3rd indicator lamp (e.g for dual trailer operation)
	NC contact/changeover contact	L	Left-side turn-signal lamp
81	Input	R	Right-side turn-signal lamp
81a	1st output, NC side		
81b	2nd output, NC side		
	NO contact		
82	Input		
82a	1st output		
82b	2nd output		
82z	1st input		
82y	2nd input		
	Multi-stage switch		
83	Input		
83a	Output, position 1		
83b	Output, position 2		
83L	Output, position left		
83R	Output, position right		

References

[1] EN 60617: Graphical symbols for diagrams.

Part 2: Symbol elements, qualifying symbols and other symbols having general application.

Part 3: Conductors and connecting devices.

Part 4: Basic passive components.

Part 5: Semiconductors and electron tubes.

Part 6: Production and conversion of electrical energy.

Part 7: Switchgear, controlgear and protective devices.

Part 8: Measuring instruments, lamps and signalling devices.

Part 9: Telecommunications: Switching and peripheral equipment.

Part 10: Telecommunications: Transmission.

Part 11: Architectural and topographical installation plans and diagrams.

Part 12: Binary logic elements.

Part 13: Analogue elements.

[2] EN 81346: Industrial systems, installations and equipment and industrial products – Structuring principles and reference designations.

Part 1: Basic rules.

Part 2: Classification of objects and codes for classes.

[3] DIN 72552: Terminal markings for motor vehicles;

Part 1: Scope, principles, requirements.

Part 2: Codes.

Part 3: Examples for application on circuit diagrams.

Part 4: Summary.

Electronic control unit (ECU)

Functions

Digital technology with programmable controllers has revolutionized automotive engineering. A whole range of functions can be realized with this technology. Many influencing factors are taken into account in the control of the systems in the vehicle. Engine management, for example, performs the entire open- and closed-loop control of the engine (e.g. ignition and fuel injection) and of many assemblies in its periphery (e.g. exhaust-gas turbocharging, exhaust-gas recirculation). Without these possibilities it would not be possible to adhere to current emission limits and low consumption figures under high engine-performance conditions.

Microcontrollers with high computing-capacity requirements are required for electronic open-loop control of systems. The electronic components are accommodated in an electronic control unit (ECU). The number of ECUs has increased sharply in the last few years; more and more systems are being electronically controlled. Some more examples are the ECU for driving-dynamics control, the vehicle-electrical-system ECU, the air-conditioning ECU, and the door ECU.

Compared with the engine ECU the range of functions and the derived performance e.g. with regard to the door control unit, which controls the power-window drives, are low.

All ECUs operate according to the same principle. The ECU detects signals from sensors and control elements, evaluates them, and activates actuators (Figure 1).

Requirements

Operating conditions

High demands are made of ECUs. They are exposed to different loads, depending on their installation location. Thus, an engine ECU installed in the engine compartment is subject to influences that are quite different from the door control unit installed in the passenger compartment. ECUs may be exposed to the following loads:

- ambient temperatures from -40°C to $+125^{\circ}\text{C}$,
- temperature changes,
- vibrational accelerations up to 20 g,
- moisture influences,
- operating fluids such as oil, fuel and brake fluid.

The following additional demands are made of ECUs:

- operational reliability in the event of voltage fluctuations in the vehicle electrical system (e.g. voltage drop when cold starting),
- power dissipation up to 70 W,
- electromagnetic compatibility (resistance to electromagnetic radiation and low radiation of high-frequency interference signals).

Range of functions and data-processing speed

The performance of the electronic components used in an ECU is increasing continuously and facilitates ever more complex control algorithms. This applies particularly to the engine-management system, which must take ever more stringent emission limits into consideration. In response to new requirements the range of functions and thus the demand for memory capacity are increasing continuously, while the trend is toward ever-decreasing external device dimensions. Development is therefore heading towards greater functional integration and to miniaturization of both electronic and mechanical components such as plug-in connections.

The increasing range of functions is accompanied by an increase in data-processing speed. All functions must be executed within a specified timeframe. Added to this is that fact that many program sections must be executed in real time so that the processes in the ECU keep pace with the physical processes (real-time capability).

All this has in the last few years resulted in the use of ever more powerful microcontrollers with increasing computing speed and greater memory resources. At the beginning of the 1990s 32 kByte for the program memory, 8 kByte for the data memory and 12 MHz clock frequency were sufficient for an engine-management system. Present-day engine ECUs now require 4 MByte program memory, 128 kByte data memory and a clock frequency of 270 MHz. And development continues apace, with numerous microcontrollers being used in ECUs in the future (multicore computers).

ECU components

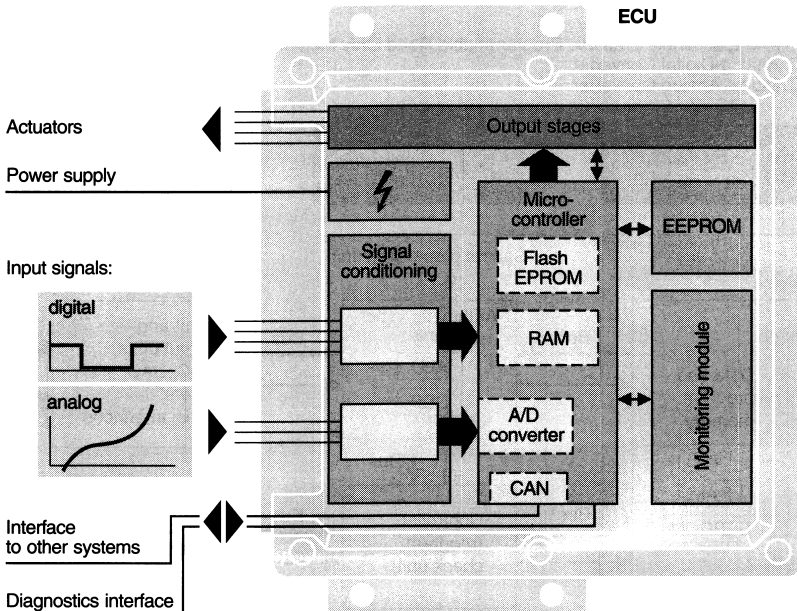
The ECU is the control device of an electronic system. It detects the operating conditions via sensors, processes them and activates actuators. Signal processing takes place in the ECU's computer core.

Computer core

Microprocessor

The microprocessor represents the integration of a computer's central processing unit on a single chip. Microprocessor design ensures that units can be programmed to meet the varied requirements associated with specific operating conditions. There are two different main groups of processor. Earlier PCs (personal computers) used CISC processors (CISC: Complex Instruction Set Computing). A very large amount of special commands which are executed in a specific number of clock pulses is implemented in these processors.

Figure 1: Signal processing in the ECU



RISC processors (RISC, Reduced Instruction Set Computing) are usually used in ECUs, i.e. also in vehicle ECUs. The advantage of RISC processors lies in the fact that the commands usually only require one clock pulse and can be implemented by the simpler and faster commands of higher-performance systems.

Today's RISC processors with more than 300 commands have more commands than older CISC processors, therefore the more accurate difference between CISC and RISC is the mean number of clock pulses for a command and no longer the number of commands.

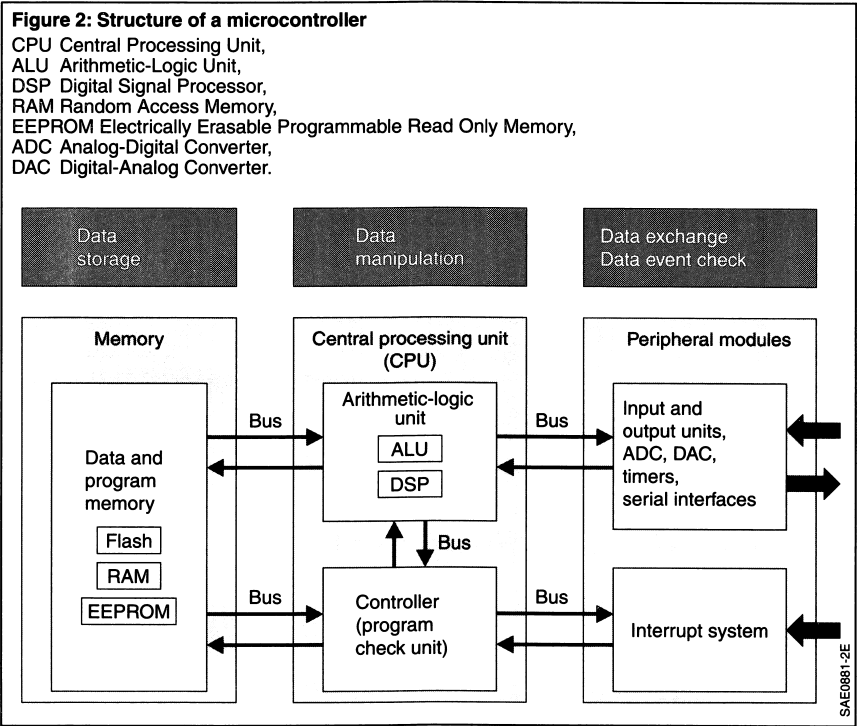
A microprocessor cannot usefully operate by itself; it always acts as part of a microcomputer.

Microcomputer

A microcomputer consists of a microprocessor serving as the central processing unit (CPU). The microprocessor contains

the controller and the arithmetic-logic unit (Figure 2). The arithmetic-logic unit performs arithmetic and logic operations and operations involving digital signal processing, while the controller retrieves the commands and data from the memory. Pipeline stages, which preprocess the commands and data (e.g. retrieval of instructions and data, writing of data), are used to achieve higher clock frequencies. The arithmetic-logic unit is integrated in the pipeline.

The program memory (ROM, Read Only Memory; PROM, Programmable Read Only Memory; EPROM, Erasable Programmable Read Only Memory, or Flash EPROM) contains the non-volatile working program (user program) (see Program and data memory). The data are still available after switching on again even when there is no supply voltage. In current applications the program memory is usually a flash EPROM.



The data being run at any given time are stored in the data memory. These data change, and are stored in a RAM (Random Access Memory).

A cache as a high-speed buffer memory for program and data memories (in series production in Bosch engine-management systems since 2006) can be integrated on the microcomputer. If the required commands and data were always sent over buses and there were no cache, the high data rates (which the processor needs for working) and the relatively slow access to the memories would drastically reduce CPU speed and there would be no use in deploying a high-speed processor.

The bus system links the individual elements in a microcomputer. A clock generator makes sure that all the operations in the microcomputer take place within a specified timeframe.

Logic circuits are chips that carry out special tasks, such as for interrupts (interrupt) or the reset logic (to reset the microprocessor). Input and outputs units (I/O) are required to connect with the peripherals. The peripherals include, for example, inputs for the crankshaft and camshaft signals, operating switches, analog inputs, and power drivers such as H-bridges or switches.

Microcontroller

In-car applications are subject to the requirement that the sequence of the ECU program keep pace with the physical sequences. Thus, system must respond within the shortest possible time to, for example, changes in input signals. The systems must therefore have "real-time capability". The function of the timer unit is to encapsulate the real time. There are two basic principles here – capture and compare.

The capture function for input signals assigns a time or angle stamp (angle as reference for example to the crankshaft) to the events at the input and stores the capture values in registers. Thus the processor does not have to process the signal further immediately; it can first close the running software routine and then process the capture values.

The compare function for output signals generates an event (e.g. switching of the

ignition coil at the moment of ignition) at the output pin at a specific time or angle. These values are stored beforehand in registers.

Microcomputers which have real-time capability are called microcontrollers. Nowadays they are typically integrated on a chip and are not, as in the past, designed as discrete components on the printed-circuit board. This is possible due to the fact that highly complex systems can be integrated on a chip thanks to modern technologies.

For future applications it will no longer be sufficient to have just one CPU, since the clock frequency cannot be increased in any way the user likes and this also results in very high current inputs. For this reason, microcontrollers will come in variants containing more than one CPU (more than five CPUs on one chip for Bosch engine-management systems, to be produced in series from 2015) – the same trend as with PC systems.

The microcontrollers which are used in the automotive industry differ from standard microcontrollers on various points.

- Temperature range: Junction temperature from -40 to 165°C .
- Failure rate: Less than 1 ppm (one failure per one million components) – compared with 100 to 200 ppm for PCs.
- Service life: This is current specified at 40,000 hours in active operation (this corresponds in the case of a PC that is switched on for eight hours a day to an operating period of approx. 14 years).
- Significantly longer availability: Whereas no new microcontrollers have to be subsequently delivered for cellular phones and PCs after a production cycle of 1–3 years, complex projects in the automotive field start series production only after 3–5 years development, after which they remain in series production for a period of 15 years and are then subsequently delivered for a further 15 years.

Semiconductor memories

Memory principle

Data storage comprises the following operations: recording (writing), permanent storage (data storage in the narrow sense), retrieval, and output (reading) of information. Figure 3 provides an overview of the different memory types. The memory operates by exploiting physical properties that facilitate unambiguous production and recognition of two opposed states (binary information). In semiconductor memories the states produced are either “conductive” and “nonconductive” or “charged” and “discharged”. A technology in frequent use today is the flash memory. Memories operating according to this principle are electrically programmable and erasable.

New memory types will also be used in the future. The FRAM (Ferroelectric Random Access Memory) with the ferroelectric memory principle, the MRAM (Magnetoresistive Random Access Memory) with the magnetic effect as the memory principle, and the PCM (Phase Change Memory) utilizes as its memory effect the change of state of a material from crystalline to amorphous and the associated change in resistance. MRAMs and PCMs have the potential to supersede the flash memories (non-volatile but slow) and RAMs (fast but volatile) used today, since they retain their data after the power supply is switched off and also have very short access times (not to be introduced in engine management prior to 2020).

Program and data memory

The microcontroller requires a program – the software – for the calculations. It is stored in a non-volatile program memory. The CPU reads out the values, interprets them as commands, and executes these commands in order.

Variant-specific data (individual data, characteristic curves and program maps) are additionally stored in this memory. The software can be adapted to different vehicle variants (e.g. different ignition maps) with these data.

The software requires a read/write memory to store variable data (variables) such as e.g. computing values.

Flash memory

The flash EPROM has superseded the conventional EPROM erasable with UV light (Erasable Programmable Read Only Memory) as the program memory. It is electrically erasable so that the ECU can be reprogrammed in the service workshop without it having to be opened. The ECU is connected via a serial interface to the reprogramming station.

RAM

All the variable data calculated in the software are stored in the RAM (Random Access Memory, i.e. in a read/write memory). The memory capacity of the RAM integrated in the microcontroller is not enough for complex application such that an additional RAM chip is required. It is connected via the address bus and the data bus to the microcontroller.

The RAM loses the entire data stock (volatile memory) when the ECU is disconnected from the supply voltage. The RAM is permanently supplied with voltage to prevent adaptation values learned during vehicle operation from being lost when the ignition is switched off. These values are however lost when the battery is disconnected.

EEPROM

Data that change in vehicle operation and which must not be lost when the battery is disconnected (e.g. important adaptation values, codes for the immobilizer) must be stored in a non-volatile memory (e.g. EEPROM).

It is also possible to use separately erasable areas of the flash EPROM as a non-volatile data memory for these data. An EEPROM is emulated in the flash (in separate areas – outside the program and data memory) for this purpose. The current data in each case are written to the end of a table, which gradually fills the blocks of the flash area. The old data can then be completely erased with the block. This ensures that the correct data are in the memory even when the supply voltage is disconnected.

Monitoring module

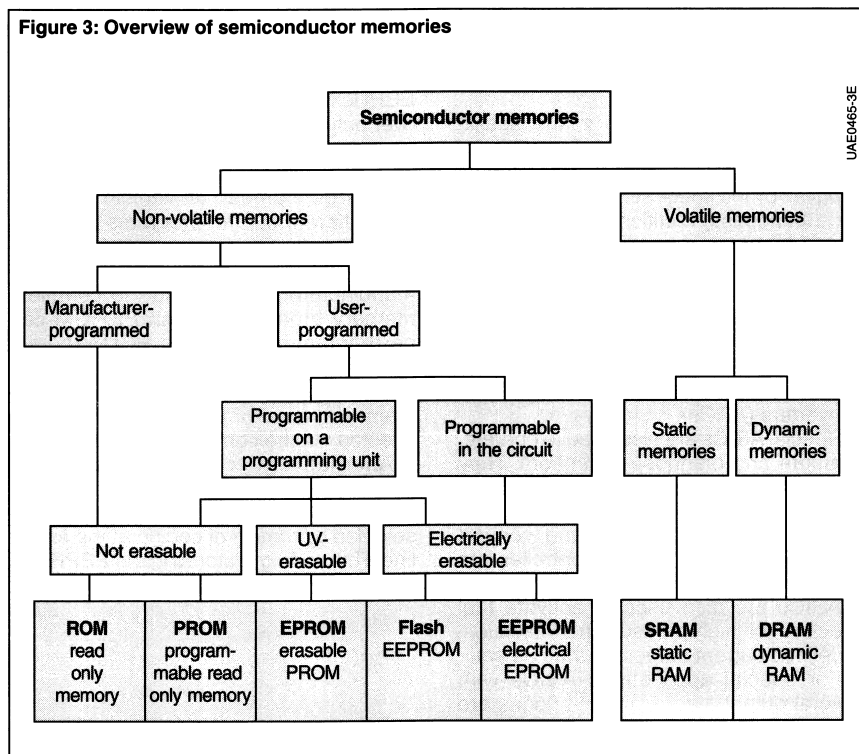
A monitoring module is required for safety-relevant systems. This is effected by a logic circuit in the voltage regulator (e.g. for engine-management systems) or in a separate integrated circuit (e.g. for transmission management). The monitoring module can also be effected by a separate computer.

The microcontroller and the monitoring module use a "question-and-answer game" to monitor each other. When a fault is detected, the ECU of both is rendered safe independently of each other – in the case of engine management e.g. by the deactivation of torque-relevant output stages.

Voltage regulator

The electronic components in the ECU need a stable voltage of 5 V. Some applications also require further voltage values, e.g. 3.3 V. The voltage regulator maintains the battery voltage, which can be 6 to 16 V depending on the battery state and load, at these constant values. Suppressor circuits suppress high interference voltages from the vehicle electrical system.

The voltage regulator contains an enabling logic which ensures that the voltages run up under defined conditions and then enable resets. This ensures that the microcontroller runs up under defined conditions after the supply voltage is switched on.

Figure 3: Overview of semiconductor memories

ASIC chips

ASIC chips are application-specific integrated circuits. They are designed and produced in accordance with the specification of ECU development. Integrating a large number of functions in an IC reduces the space requirement, reduces manufacturing costs and increases operational reliability.

Thus, for example, the power supply for the ECU and several power output stages with the associated diagnostic circuits can be integrated on one chip. An example of this is the "U-chip", which features on one IC a power supply, the monitoring module, serial interface drivers and output stages, and an H-bridge with diagnostics.

Another function of an ASIC module is, for example, to relieve the load on the microcontroller or to make additional hardware available (e.g. additional input and output channels for static signals and for PWM signals).

An ASIC can be used in the spark-ignition engine-management system for knock control which boosts the signals supplied by the knock sensors, filters them via a bandpass, rectifies them, and integrates them via a specified crank-angle window. The microcontroller then only has to read out the integrated voltage value at the end of the window. However, in newer ECU generations the knock-sensor signals are detected directly by the microcontroller via high-speed analog-digital converters (ADCs).

Special ASICs are also used to operate, evaluate and diagnose λ sensors. They activate the sensors with defined signals, evaluate currents, voltages and temperature with great precision, and convert these signals for the microcontroller into digital input signals.

ASICs are also used to activate fuel injectors for high-pressure fuel injection. A defined current curve can thus be set.

For special applications ASICs with several output stages and H-bridges are available which also contain a diagnostic function and can be activated via a serial bus.

Communication

The peripheral components communicate with the microcontroller via the address bus and the data bus. The microcontroller outputs via the address bus for example the RAM address whose memory content is to be read. The RAM chip then places the data on the data bus, on which they can be read by the microcontroller.

To save on pins on the components, the addresses and the data are output in the multiplex process. Address bus and data bus use the same lines. First the address is applied to the bus, then the data are transmitted.

Communication with the ASICs is effected via SPI (Serial Peripheral Interface) or via MSC (Micro Second Channel). Ports can thus be saved on the microcontroller in the case of output stages.

Data which do not require a high bit rate (e.g. fault-memory data stored in the EEPROM) are also serially transferred over only one data line.

EOL programming

The large number of vehicle variants with different control programs and data records calls for a procedure for reducing the ECU types required by the vehicle manufacturer. To this end the complete memory area of the flash EPROM can be programmed with the ECU program and the variant-specific data record at the end of vehicle production with EOL programming (End of Line). Data transfer is effected via the communication interface.

Alternatively, to reduce the variant diversity in the memory, it is possible to store several data variants which are then selected by means of coding at the end of line. This coding is stored in the EEPROM.

Data processing

Input signals

Control elements and sensors form the interface between the vehicle and the ECU. The electrical signals are supplied to the ECU via the wiring harness and connectors over different interfaces.

Analog interface

Physical quantities such as the engine temperature or the intake-manifold pressure are forwarded by sensors as analog measured values to the ECU. These input signals can assume any voltage value within a certain range. They are converted in the microcontroller by an analog-digital converter (ADC) into a digital value. The typical resolution of the integrated converters is 10 bits. These 1,024 stages deliver for a reference voltage of 5 V a typical resolution of approx. 5 mV.

In future sensors which detect analog values will increasingly incorporate additional electronics which digitize the analog value locally and output the measured value via a digital interface. One of these interfaces is PSI5, on which data can be transferred bidirectionally (see PSI5).

Digital interface

Digital input signals have just two states "High" (logic 1) and "Low" (logic 0). They can be evaluated directly by the ECU. Examples of digital signals are switching signals of control elements, speed signals from a Hall-effect sensor (for measuring wheel speed or engine speed), or static signals from a Hall-effect sensor (e.g. position sensor in the transmission).

Signal conditioning

The input signals are limited by suppressor circuits to permissible voltage levels. Filters remove most of the superimposed noise from the useful signals, which are then amplified if necessary to the microcontroller's permissible input voltage (0–5 V).

Special ASICs for signal conditioning are used (see ASIC chips) for some sensors, such as λ sensors.

Signal processing

The ECU is the control center for the functional sequences of an electronic system. The control algorithms run in the microcontroller. The input signals provided by the sensors and the interfaces to other systems for example via the CAN bus serve as input variables. They are checked for plausibility again in the microcontroller. The algorithms are processed with the aid of the ECU program (software). The ECU program is stored in the read-only memory (e.g. flash EPROM), the calculated intermediate values are stored in the data memory (RAM). The software calculates the output signals to activate the actuators.

Output signals

The microcontroller uses the output signals to activate output stages, which deliver sufficient power for direct connection of the actuators. Several output stages can be integrated in a single ASIC. Consumers with high currents to be switched (e.g. engine fans) are switched via relays or with output stages directly on the assembly.

Signal types

Switching signals

Switching signals are used to switch actuators on and off, depending on the current operating point (e.g. fuel injectors, engine fans).

PWM signals

Digital output signals can be output as a PWM signal (pulse width modulation) with constant frequency and variable on-time. Actuators such as the exhaust-gas recirculation valve, the throttle valve or the charge-pressure actuator can, depending on the clock ratio, be moved into any operating positions.

Application-specific output stages

Some actuators require special current and voltage curves for operation. Examples of such are the activation of high-pressure fuel injectors for gasoline direct injection (see High-pressure fuel injector) or for common-rail injectors (see injectors). The actuators are activated by complex output-stage modules with integrated control logic and analog signal conditioning. These modules deliver a high voltage during switch-on, with the high making current producing a fast breaking operation. The system is then regulated back to a lower holding current.

Switching variants

There are different switching variants for activating the actuators. Low-side output stages control inductive and ohmic loads which are connected to the battery voltage (e.g. valves, relays, ignition coils). High-side output stages switch consumers which are connected to ground. DC motors are activated via bridge-type output stages; here, both connections of the motor are switched by the ECU. This makes it possible to reverse the direction of rotation (e.g. power-window drives, activation of the throttle valve).

Self-protection function

The output stages are protected against short-circuits to ground, against short-circuits to battery voltage, and against being destroyed due to electrical or thermal overload. These malfunctions and interrupted lines are detected as faults by the output-stage IC and signaled to the microcontroller via a serial interface.

Communication interfaces

The ECU has one or more communication interfaces for communicating with other electronic systems. In this way, for example, the driving speed can be sent by driving-dynamics control to all the systems that need this signal (e.g., the instrument cluster for displaying the driving speed). The signals therefore only have to be calculated one in the ECU network. Data transfer is effected via bus systems (see Automotive networking, buses in the vehicle).

Automotive software engineering

Motivation

Aim of development

Any development has the aim of creating a new function or improving an existing function of the vehicle. Such functions bring about an added value for the user of the vehicle (e.g. occupants, mechanics in the workshop or haulage contractors), compliance with statutory requirements, simplified maintenance, or improved development or manufacturing efficiency. Technical implementation can be mechanical, hydraulic, electrical or electronic. Often it is combinations of these technologies, where electronics increasingly plays a key role in the realization of many innovations in a motor vehicle. Thanks to the use of electronics, electronics and software – the logical core of systems – “intelligent” functions of the drive, the chassis and the rest of the vehicle are cost-effectively realized.

Virtually all vehicle functions in all vehicle classes are now electronically controlled or monitored. Ongoing advances in the technology and performance of electronics hardware allow the realization of many new, more powerful functions through the use of software. The various electronic systems are being increasingly cross-linked in the vehicle. Efforts are pursuing cross-linking vehicles to each other and with the environment (e.g. Internet).

Software requirements

The specific requirements of the software are highly varied. Many systems for the engine and for driving safety must operate with “real-time capability”, i.e. the response of the control operation must keep pace with the physical process. When very fast physical processes are being controlled, such as for example engine management or driving-dynamics control, the calculation must therefore be made very quickly. Even the requirements with regard to reliability are high in many fields. This is particularly true of safety-relevant functions. The software and the electronics are monitored by complex diagnostics.

The software is used across the many variants of a vehicle or even across model series. It must then be adaptable to the corresponding destination system. It contains calibration parameters and program maps for this purpose. These amount to several 10,000 per vehicle. These manipulated variables are dependent on each other in many ways. In addition, a functionality is distributed beyond multiple systems or control units more and more frequently.

The software is for the most part developed specially for the corresponding applications and is integrated into the entire system. It is called “embedded software”. The many functions are often developed and further developed over a long period of time in many locations around the world. Because spare parts must remain available even after the production of a particular vehicle has come to an end, the electronics in the vehicle must have a relatively long life cycle of up to 30 years.

For cost reasons, ECUs often contain microcontrollers with limited computing power and limited memory space. This requires optimization measures in software development to reduce the hardware resources required.

The characteristic features of software differ depending on the field of application. While the software for the drivetrain is extensive, the emphasis is on real-time performance in the chassis applications. In safety and comfort and convenience applications, the emphasis is on efficiency, i.e. the consumption of resources, and in multimedia applications large volumes of data must be processed in a short period of time.

The complexity resulting from these requirements and features must be economically mastered in a cooperation of development between vehicle manufacturers and suppliers.

Design of software in motor vehicles

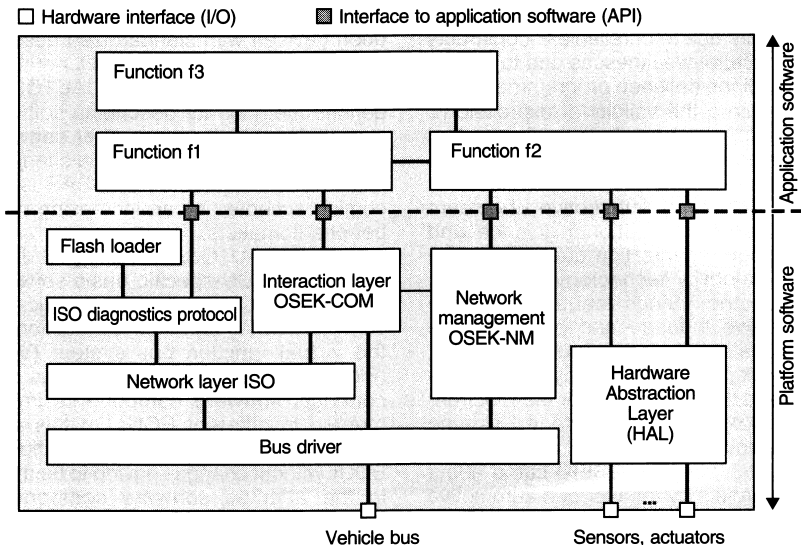
The software in a motor vehicle is made up of many components. A distinction is essentially made, as is the case with a PC, between the “perceptible functions” of the software, the application software and platform software partly dependent on the hardware (Figure 1). The interaction between all the functions is defined in the architecture. Different views can be adopted here. The static view describes hierarchically the function groups, the signals and the distribution of the resources. On the other hand, the functional view describes the signal progression through the different functions. The dynamic, i.e. time-dependent view, considers the time response in the execution of the various tasks. Standards have already been introduced at an early stage to ensure the interaction between and further development of the individual components. The most important standards are explained in the following.

Important standards for software in motor vehicles

Bodies/committees

The “Association for Standardization of Automation and Measuring Systems” (ASAM) is a standardization body in the automotive industry for data models, interfaces and syntax specifications [5]. The ASAM developed different standards for connecting an ECU to a computer or a data-entry terminal. The standard ASAM-MCD1 (MCD stands for Measurement, Calibration and Diagnosis) supports different data transport protocols for this purpose. By using ASAM-MCD2 specifications, the binary data in the ECU can be addressed and the relevant quantities can at the same time be displayed in connected tools as physical values and processed. The standard ASAM-MCD3 also permits an automation of such processes, for example for the automatic calibration of data records. Further ASAM standards cover, for example, the exchange of functional descriptions and data.

Figure 1: Main component parts of the static software architecture for microcontrollers and standardized software components



The FlexRay Consortium developed the specification for the FlexRay field bus for open and closed-loop control in the automobile field. Thanks to high transfer rates with predefined bus arbitration and a fault-tolerant design it is particularly suitable for use in active safety systems and in the drivetrain (see FlexRay).

The International Electrotechnical Commission (IEC) is an international standardization body in the fields of electrical engineering and electronics [6]. The IEC offers three evaluation systems with which conformity to the international standards can be verified. The IEC works in close cooperation with the International Organization for Standardization (ISO) [7], the International Telecommunication Union (ITU) and numerous standardization bodies (including the Institute of Electrical and Electronics Engineers, IEEE) [8].

The Motor Industry Software Reliability Association (MISRA) is an organization in the automotive industry that devises rules for the reliable development and application of software in vehicle systems [9]. The most widely known is the programming standard MISRA-C, which was developed by the MISRA. It prescribes programming rules for reliable programming in the programming language C. The purpose of this standard is to avoid runtime errors due to unreliable C constructs and structural weaknesses due to misunderstandings between programmers, and to safeguard the validity of expressions. Many rules can be automatically checked and taken into account in the generation of codes.

The Society of Automotive Engineers (SAE) is an international science and technology organization operating in the field of mobility technology [10]. It sets among other things standards for the automotive industry and promotes the exchange of knowledge and ideas.

The standardization body "Open Systems and their Interfaces for the Electronics in Motor Vehicles" (Offene Systeme und deren Schnittstellen für die Elektronik im Kraftfahrzeug, or OSEK) came about from a project by the German automotive industry. Later came the "Vehicle Distributed Executive" (VDX) initiative of the French automotive industry. Standardiza-

tions of basic-software components are established under the term OSEK/VDX in the following fields [11]:

- Communication (data exchange within and between ECUs)
- Operating system (real-time execution of ECU software and basic services for other OSEK/VDX modules)
- Network management (configuration and monitoring).

The Japan Automotive Software Platform and Architecture (JasPar) is an initiative for reducing costs and developing technology in automotive electronics. It encourages Japanese companies to develop jointly non-competition-relevant technologies such as network solutions, service functions and basic software. JasPar works in close cooperation with AUTOSAR and FlexRay.

AUTOSAR

AUTOSAR (Automotive Open System Architecture) [12] is a development partnership of vehicle manufacturers, ECU manufacturers and manufacturers of development tools, ECU basic software and microcontrollers. The aim of AUTOSAR is to simplify the exchange of software on different ECUs. To this end, a standardized software architecture has been devised with standardized description and configuration formats for embedded software in automobiles. AUTOSAR defines methods for describing software in vehicles which ensure that software components can be reused, exchanged, scaled and integrated. AUTOSAR is becoming accepted by an increasing number of automakers.

Crucial to AUTOSAR is a logical distribution into ECU-specific basic software (BSW) and ECU-independent application software (ASW) and their connection via the virtual function bus system (VFB) (Figure 2). This virtual function bus also connects software components implemented in different ECUs. In this way, these can be shifted between different ECUs without changes having to be made in the affected software components themselves. This can be useful in optimizing computing power, memory requirements or communication load.

The functional software components (SWC) are strictly separated from each other and from the basic software. They typically contain specific control algorithms executed at run time, the “runnable entities”. They communicate via the AUTOSAR interface with other functions and the ECU Interfaces. These interfaces (API) are defined in SWC XML descriptions.

The run-time environment (RTE) provides the communication services between the functional software components and the corresponding basic software on the ECU. The RTE is tailored to the specific ECU and the application. It can be generated to a large extent automatically from the interface requirements.

The basic software contains the ECU-specific program parts, such as the communication interfaces, diagnostics and memory management. The basic software also contains the service layer. This software combines software components for general service functions (SRV), communication (COM) and the operating system partly dependent on the ECU used (OS) [4, 11]. The latter is based on the OSEK/VDX OS. In this field, the resources

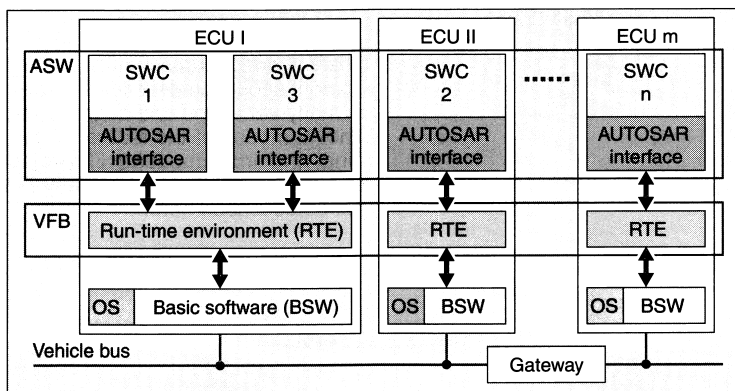
of the ECU are subdivided and managed so as to arrive at optimal network support, memory management, diagnostics, etc.

The hardware used is encapsulated in two layers based on each other. Abstraction of the microprocessor (Micro-Controller Abstraction Layer, MCAL) with direct access to the interface modules of the ECU continues in a further layer (ECU Abstraction). “Complex Device Drivers” (CDD) facilitate direct access to microcontroller resources for applications with special functionality and timing requirements. They are also an integral part of the basic software such that the application software can be developed independently of the hardware, even when the services of the complex device drivers are required.

In addition to the ECU architecture, the development methods are also standardized in part by AUTOSAR. This relates, above all, to the structure and the dependencies of the different work products (e.g. files). These are needed in order to generate from the different software component descriptions executable programs for the respective ECUs.

Figure 2: AUTOSAR architecture

ECU Electronic control unit, ASW Application software, SWC Software components, VFB Virtual function bus, RTE Run-time environment, BSW Basic software, OS Operating system.



Diagnostic standards

Vehicle-specific systems for diagnostics for vehicle development and production and for workshops prove to be high-maintenance, cost-intensive and inflexible. They tie the manufacturers to suppliers and prevent simple data communication in the case of cross-company cooperations. Some diagnostic standards have therefore been developed (e.g. [13] and [14]).

The Automotive Electronics working group (ASAM-AE) [5] has devised three specifications for data-based (i.e. software-based) vehicle diagnostics which are published as international standards in the ISO 22900 standard group [15]:

- Interface between run-time environment and communication hardware (MCD-1D and PDU-API, ISO 22900).
- ODX standard for exchange of diagnostic data, e.g. for supplying the workshop tester with data (MCD-2D, ISO 22901, [16]).
- Object-oriented programming interface (MCD-3D, ISO 22900) for diagnostic applications, such as e.g. prompted troubleshooting.

The MCD-1D standard takes into consideration existing standard tools such as, for example, devices for flashing ECUs.

Requirements with regard to an exchange format, the "Open Test Sequence Exchange Format" (OTX), are currently being defined within the framework of an ISO draft in order to create, use and exchange diagnostic sequences.

The development process

The focal point of software development is the depiction of the logical system architecture in a concrete software system with all programs and data. Here, the entire processor-controlled system of the vehicle is considered. Particular importance is attached to a clear separation of specification, design and implementation. Specification of the software functions is performed on the physical level, while design and implementation of programs and data are geared towards the specific microcontroller.

In order to satisfy the above-mentioned requirements in the development of software in automobiles, the defined sequences (processes) are, in addition to the technology and the tools, an integral part of development.

Process description models

Numerous more or less complicated models are used to describe the workflows in software development. They serve to make the sequences transparent, to compare them, to identify problem areas, and to verify conformity in accordance with defined standards. They were, however, not originally conceived to improve directly the quality of the software itself, to increase efficiency or to eliminate systematic faults in the sequences. Process description models are therefore only partly suitable. The common V model will be described here by way of example.

Principle of the V model

The V-shaped representation of the development sequence described here is used in many variations and degrees of detail. The "V model" of the federation for planning and implementing IT projects of central government in Germany [17] will not be described here.

The V model divides the process steps associated directly with development along a V, where the x -axis depicts the development progress and the y -axis the depth, i.e. the degree of detail, of the corresponding process step (Figure 3). A process step can be described by the required input variables, the procedure, the methods, the roles, the tools, the quality criteria, and the output variables. The process steps defined on the left arm are verified on the right arm. These steps can also run several times or be divided.

In the extended V model, accompanying processes such as, for example, request, change, project and quality management, can be considered.

Process evaluation models

Process evaluation models provide, in addition to a pure description of the tasks and sequences, information on the maturity and the quality of the processes. Work steps can thus be compared, evaluated and certified. In this way, it is also possible to identify process gaps which impact, for example, on the product qual-

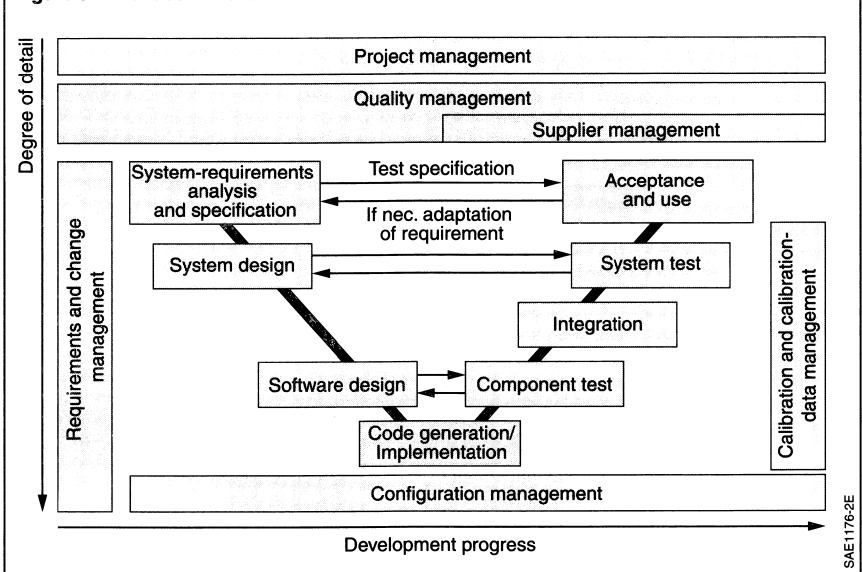
ity or the costs. However, the information on the quality of the processes does not provide a complete picture of the quality of the products themselves here either. The three most important process evaluation models will be described here.

ISO 9000 and ISO/TS 16949

The process-oriented EN ISO 9000 standard series [18] and following stipulates the requirements with regard to a quality management system. The focus here is on the interactions and the interfaces. The original emphasis was on production and the customer interfaces.

The ISO/TS 16949 technical specification [19] was devised in the North American and European automotive industries and standardizes requirements relating to quality management systems. The aim of the standard is to improve effectively system and process quality in order to increase customer satisfaction, to identify failures and risks in the production process and in the supply chain, to eliminate their causes, and to check the effectiveness of the corrective and preventive ac-

Figure 3: Extended V model



tions taken. The core of the specification is not the discovery, but rather the avoidance of failures.

Compliance with ISO 9000 and ISO/TS 16949 can be verified by certification.

CMMI

“Capability Maturity Model Integration” (CMMI) is a model for evaluating and systematically improving development organizations and their processes [20] which was originally developed by the Software Engineering Institute (SEI). It describes a collection of requirements with regard to the processes and their dependencies (Figure 4). CMMI offers a framework, the implementation of which calls for a business-oriented interpretation

and organization of content. It describes what has to be done. The organization must shape the “how” appropriately. The content of CMMI is based on essential industry “best practices”. CMMI provides a procedure for process improvement created in the longer term from the path of organization development through to learning organization.

CMMI has much in common in terms of content with ISO 9000 and ISO TS 16949. In this context, CMMI has a higher degree of detail, while ISO 9000 and ISO TS 16949 cover a wider range of application.

CMMI distinguishes between five maturity levels (ML) for an organization unit (Figs. 4, 5). Different process areas are considered, depending on the maturity

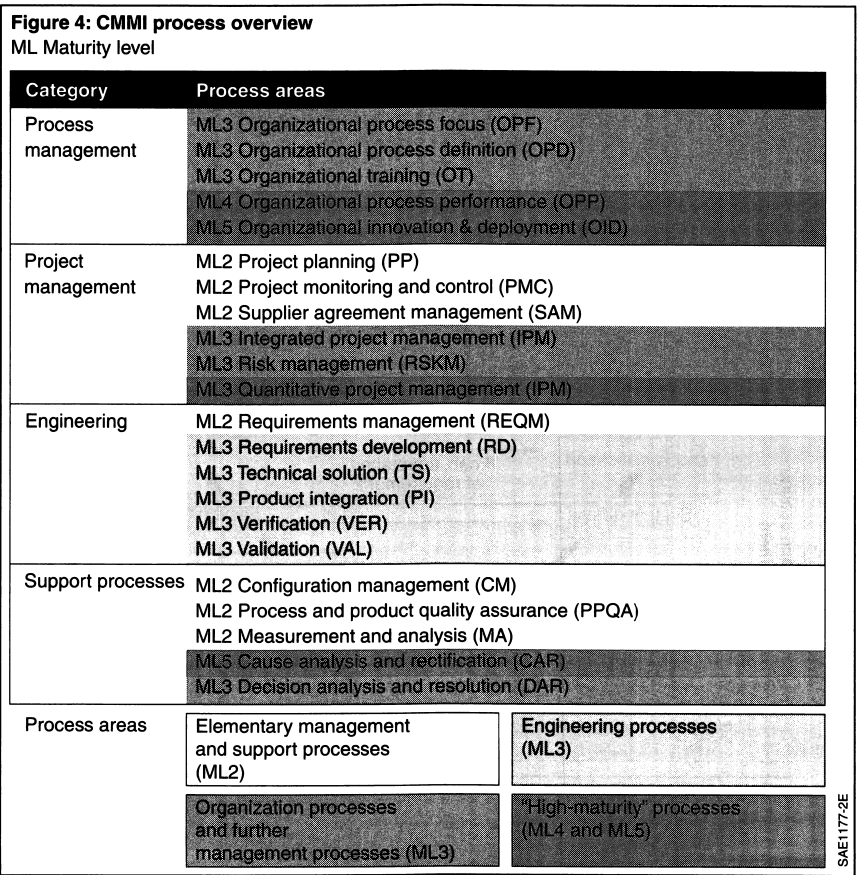
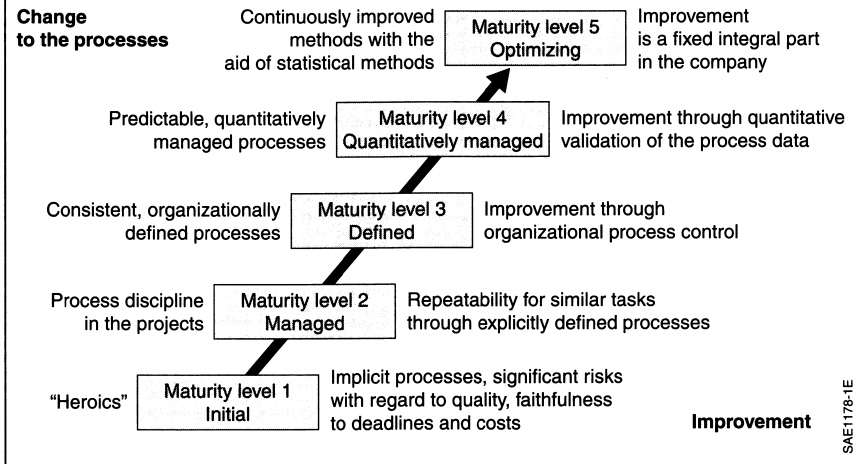


Figure 5: CMMI maturity level



level. A maturity level is reached when all the corresponding process areas are mastered and verified by an assessment. To reach a higher maturity level, the process areas of the maturity levels underneath must also be verified again.

CMMI is used as an improvement and evaluation model for development organizations and offers good support for organization-wide process optimization and auditing of suppliers.

Automotive SPICE

SPICE stands for "Software Process Improvement and Capability Determination". Automotive SPICE [21] is a motor-vehicle-specific variant of the international ISO/IEC 15504 standard (processes in the life cycle of software, [22]). It is a model for project-specific evaluation of software development processes and concentrates, like CMMI, on the requirements for systematic development. The model content of Automotive SPICE and of CMMI is therefore very similar. Automotive SPICE concentrates more on the requirements level and affords less scope for the business-oriented interpretation of requirements. Automotive SPICE focuses (currently) only on the software and only on individual projects. In contrast, the ranges of application of CMMI go further, compris-

ing development activities and services of all kinds and their direction through the organization. Automotive SPICE is used by motor-vehicle manufacturers as an evaluation model for software projects of suppliers.

The process assessments are carried out using the two-dimensional reference and assessment model. The "process dimension" serves to identify and select the processes to be analyzed in the assessment, the "maturity-level dimension" on the other hand serves to determine and evaluate their respective capability. The maturity-level dimension consists of the six maturity-level stages "incomplete", "performed", "controlled", "established", "predictable" and "optimizing".

Quality assurance in software development

As with any technical product, numerous tools for quality assurance are also used on software. In contrast to mechanics and electrics, quality assurance plays a lesser role in the manufacture of software, since software is relatively easy to reproduce. Important emphases are the overall functionality of the system, the quality standards, mastery of complexity, and application. Because the software in a motor vehicle also includes safety-relevant systems such as, for example, driving-dynamics and driver-assistance systems, the verifiability of quality plays an important role. Even the economic representation of the aimed-for software quality, especially in complex systems, is very important.

ISO 26262

Based on the IEC 61508 standard [23], the ISO 26262 standard [24] has been introduced by the automotive industry for drafting safety-related electric and electronic systems in motor vehicles. This comprises requirements relating to both the product and the development process, and thus comprises conception, planning, development, implementation, startup, maintenance, modification, shutdown and uninstallation both of the safety-relevant system itself and of the safety-related (risk-reducing) systems. The standard designates these phases in their entirety as the "entire safety life cycle". The products are subdivided into Safety Integrity Level SIL 1 through SIL 4 (ISO 61508) and Automotive SIL, ASIL A through ASIL D (ISO 26262). SIL 1 and ASIL A are the lowest, SIL 4 and ASIL D the highest safety integrity level.

Workflows of software development in motor vehicles

Interdisciplinary cooperation in development (e.g. between drive and electronics development), distributed development (e.g. between supplier and vehicle manufacturer or at different development locations) and the long life cycles of the software elements call for a common and holistic understanding of the tasks involved. For example, when designing the open-loop and closed-loop control functions of a vehicle, it is also necessary to maintain an overview of overall reliability and safety requirements, as well as the aspects of software realization. To meet these challenges, model-based development has established itself in many fields of application (Figure 6).

Model-based development

Model-based development distinguishes between two areas. The logical system architecture comprises and describes the virtual area of the models, while the technical system architecture contains the real ECUs and vehicles. The "logical system architecture" is gray in the figures and the "technical system architecture" is white. This procedure is described in terms of open-loop and closed-loop control functions, but is also suitable for general realization of functions – for example, for monitoring and diagnostic functions.

A graphics-based function model considers all system components and can be used as the basis for a general understanding. In software development, the use of model-based development methods, with notations such as block diagrams or finite state machines, is replacing written software specifications to an increasing extent. This method of modeling software functions has still other advantages. If the specification model is formally described, i.e. unambiguously and without leeway for interpretation, as a mathematical function, the specification can be executed on a computer in a simulation, and tested quickly and realistically in the vehicle itself by means of "rapid control prototyping". Inconsistencies can also be uncovered more easily.

Methods of automated code generation can be used to implement the specified function models as software components for ECUs. The function models, therefore, need to contain additional software design information. These may include optimization measures, depending on the product characteristics required by the electronic system. Automated code generation also ensures that the code has consistent quality characteristics.

In the next step, virtual environment models, which are supplemented if necessary by real components such as injectors, simulate the environment of the ECUs, facilitating "In-the-loop tests" in the laboratory. Compared to test-bench and road tests, this increases flexibility and enhances test depth, thereby making test cases easier to reproduce.

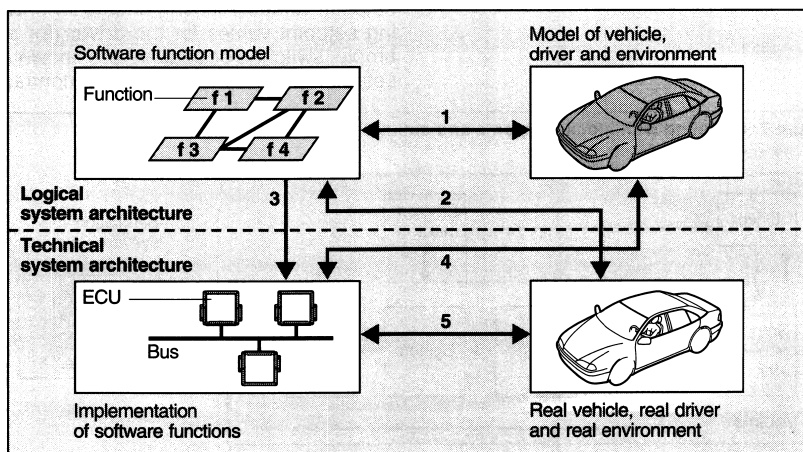
The calibration of the software functions in the electronic system must consider the vehicle-specific settings, for example, parameters stored in the form of charac-

teristic values, characteristic curves, and characteristic maps of these functions. In many cases, this matching does not take place until a later stage in the development process, frequently directly in the vehicle while the systems are running. The trend, however, is increasingly towards an earlier preliminary data feed; i.e. starting in the early development phases the most realistic calibration data possible is determined using models or empirical values. Because of the multitude of calibration variables and the mutual dependence, the calibration requires suitable procedures and tools, because in the end the quality of the calibration engineering, i.e. the exact adaptation of the software to the vehicle, decides the extent to which the potential of the software is utilized.

Efforts to shift development steps ahead are increasing, i.e. in the realm of simulated (virtual) environment, to detect faults early and save on expensive test hardware and experimental vehicles

Figure 6: Development steps in the model-based development of software functions

- Step 1: Modeling and simulation of the software functions for the ECU and of the vehicle, driver and the environment on the computer (software functions are all the functional program parts of the software),
 Step 2: Rapid control prototyping of the software functions in the real vehicle,
 Step 3: Implementation of the software functions in the real vehicle,
 Step 4: Integration and testing of the ECUs with In-the-Loop test systems, laboratory assemblies and test benches,
 Step 5: Testing and calibration of the software functions and of the ECUs in the vehicle.



(front loading). High-performance simulation tools and virtual ECU environments make this possible.

Function and ECU networks

This procedure can also be applied to the development of function networks and ECU networks. In these cases, however, additional aspects are introduced, such as:

- combinations of modeled, virtual, and functions already realized in ECU code, and
- combinations of modeled, virtual, and realized mechanical components and hardware.

It is useful, therefore, to distinguish between functions at an abstract level, and technical realization at a more concrete level. The concept of a separate abstract and concrete approach can be applied to all vehicle components, the driver, and the environment.

Modeling and simulation of software functions

Modeling

Block diagrams should be used where possible to model open-loop and closed-loop control systems. These diagrams use blocks to represent the response of components, and arrows represent the flow of signals between the blocks (Figure 7). As most of the systems are multivariable systems, all signals are generally in vector form. These are classified into:

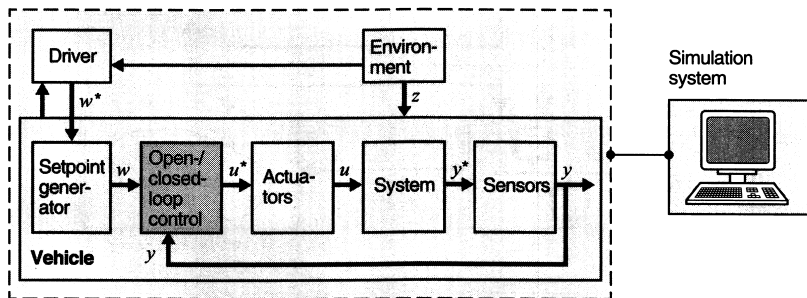
- measurement or feedback variables y ,
- open- or closed-loop control output variables u^* ,
- reference or setpoint variables w ,
- driver setpoint values w^* ,
- open- or closed-loop control variables y^* ,
- manipulated variables u ,
- disturbance values z .

The blocks are classified into:

- open- or closed-loop control,
- models of actuators,
- system model,
- models of setpoint generators and sensors, and
- model of the driver and the environment.

The driver can influence the functions of the open- or closed-loop controller by defining setpoint values. All components for entering setpoint values for the driver (for example, switches or pedals), are known as setpoint generators. Sensors, in contrast,

Figure 7: Modeling with block diagrams and simulation



record signals from the plant. A model of this type can be executed on a simulation system (for example, a PC), thus allowing it to be analyzed in more detail.

Rapid control prototyping of software functions

Rapid control prototyping in this context includes all methods for the early implementation of specifications of open-loop and closed-loop control functions in the real vehicle. To allow this, the modeled open- or closed-loop control functions must be implemented in the test. Experimental systems can be used as an implementation platform for the software parts of the open- and closed-loop control functions (Figure 8).

The experimental systems are connected to the setpoint generators, sensors and actuators, as well as the other vehicle ECUs that belong to the overall system. The interfaces to the real vehicle mean that the software functions implemented in the experimental system – and in the ECU – take into account real-time requirements.

Real-time computer systems with considerably higher computing power are usually deployed as ECUs in experimental systems. PCs are increasingly being used as the processor core for this task. This allows the model of a software func-

tion to be automatically converted from a specification into an implementable model using a rapid control prototyping tool that is subject to standardized rules. The specified behavior can then be modeled as accurately as possible.

Experimental systems with a modular structure can be configured specifically for the application, for example, in terms of the required interfaces for input and output signals. The overall system is designed for deployment in the vehicle, and is operated using a computer, e.g. a PC. This allows the testing of software function specifications directly in the vehicle at an early stage. The specifications can then be changed as required.

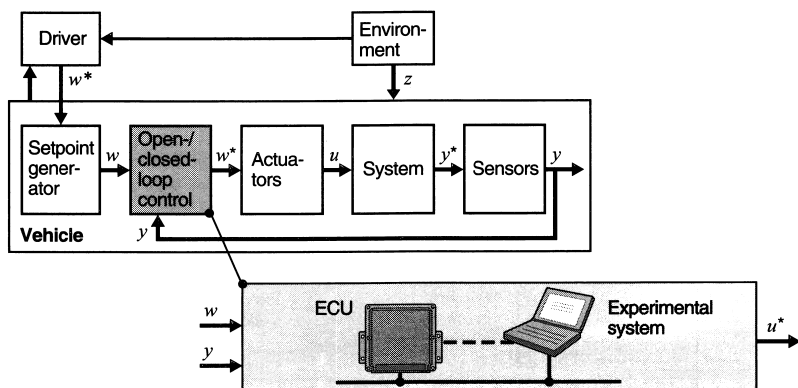
When using experimental systems, there is a choice between bypass and fullpass applications.

Bypass or fullpass applications

Bypass applications are mainly used if only a few software functions are under development, and an ECU with tried-and-true basic functionality is available – for example, from a previous project.

Bypass applications are also suitable if the sensor and actuator functions of an ECU are very complex, and supporting them requires significant effort on the part of the experimental system (for example, in the case of engine ECUs).

Figure 8: Rapid control prototyping for software functions in the real vehicle



Fullpass applications are more suitable if an ECU of this type is not available, if additional setpoint generators, sensors, and actuators also need to be tested, and if the scope of the ECU is of manageable complexity.

It is also possible to combine a bypass of individual software parts and a fullpass of the entire software. This has the advantage of increased flexibility.

Bypass applications

Bypass development is suitable for early testing of an additional or modified software function of an ECU in the vehicle. The new or modified software function is defined by a model and run on the experimental system. This requires an ECU that can run the basic functionality of the software system, support all the necessary desired-value generators, sensors, and actuators, and provide a bypass interface to the experimental system. The new or modified software function is developed using a rapid control prototyping tool. It is then run on the experimental system (Figure 9).

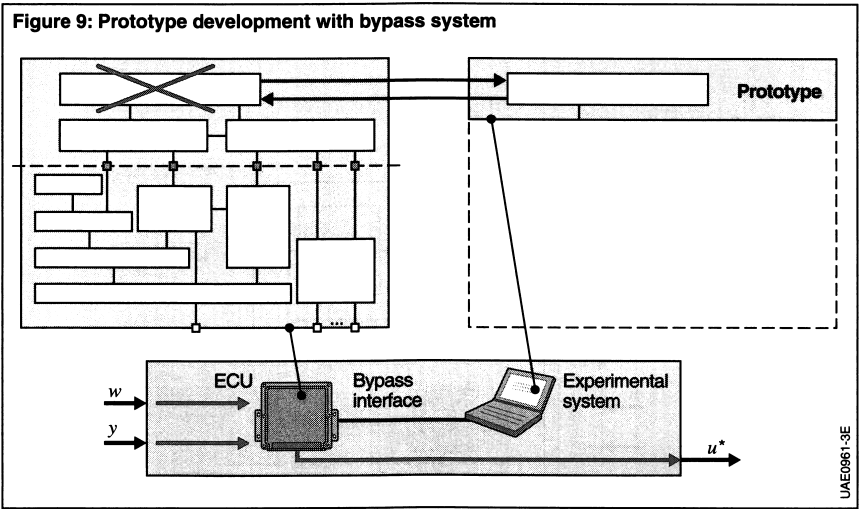
This approach is also suitable for further developments to existing ECU functions. In this case, the existing functions in the ECU are still used, but they are modified to the extent that the input values are sent via the bypass interface, and the output values from the newly developed bypass

function are used. The required software modifications to the ECU are called the bypass hooks. These can also be used in previously compiled software with modern development tools. For the essential synchronization of functional computing between the ECU and the experimental system, a procedure is normally adopted in which the ECU triggers computation of the bypass function on the experimental system via a control flow interface. The ECU monitors the output values of the bypass function for plausibility.

The bypass can also be effected via the vehicle bus (e.g. CAN). Even direct access to the CPU of the ECU via the microcontroller interfaces is possible by means of an emulator probe.

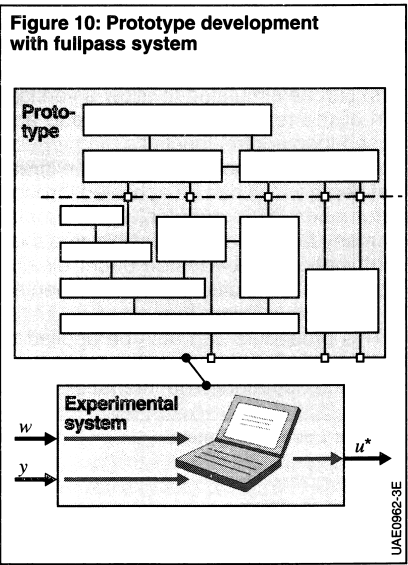
Fullpass calibration

If a completely new function is to be tested in the vehicle, and an ECU with a bypass interface is not available, the test can be carried out using a “fullpass” development. In this case, the experimental system must support all the setpoint generators, sensors, and actuator interfaces for the function. The real-time behavior of the function must also be defined and guaranteed by the experimental system (Figure 10). In general, this is performed by a real-time operating system on the fullpass computer.



Virtual prototyping

In the case of complex systems, it is advantageous to test functions as early as possible. One possibility is offered by virtual prototyping. Here the prototype is tested on a virtual environment model. The operating system of the later ECU (e.g. RTA) runs on the experimental system. This enables the time response of the later software to be considered as well.

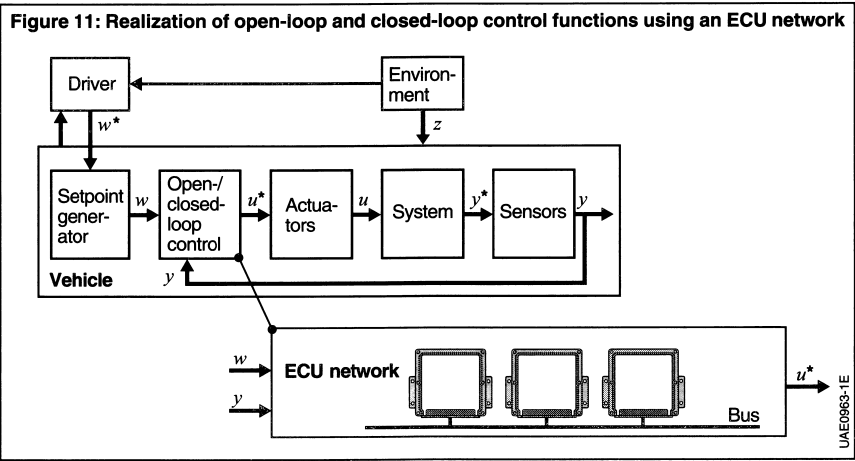


Design and implementation of software functions

Based on the specification of data, the functional behavior and the real-time behavior of a software function, all the technical details of the ECU network, the implemented microcontroller, and the software architecture must be taken into account at the design stage. The final implementation of the software functions can then be defined and executed on the basis of software components (Figure 11).

In addition to decisions regarding the design and behavior of a software function, that takes the time and discrete-related functions of the microcontrollers into consideration, an implementation includes design decisions regarding real-time behavior, distribution and integration of microcontrollers and ECUs, and reliability and safety requirements of the electronic systems. All requirements for electronic systems and vehicles from the production and service viewpoints must also be taken into account (for example, monitoring and diagnostics concepts, the parameterization of software functions, or software updates for ECUs in the field).

Generation of the code and of the accompanying data (e.g. data for documentation, variant management or preliminary data feed of the calibration) is often performed automatically in accordance with established standards.



Integration and testing of software and ECUs

Requirements

Prototype vehicles are often only available in limited numbers. It means that a component supplier often does not have a complete or up-to-date integration and test environment for the components supplied. Restrictions in the test environment can sometimes limit the possible test steps. For this reason, the environment models often serve as the basis for test systems and test benches in the integration and test phase.

Component integration is a synchronization point for all the individual component developments involved. The integration test, system test, and acceptance test cannot be carried out until all the components are available. For ECUs, this means that the software functions can only be tested when all the components in a vehicle system are available (ECUs, setpoint generators, sensors, actuators, and system). The use of In-the-Loop test systems in the laboratory allows early verifications on ECUs in a virtual test

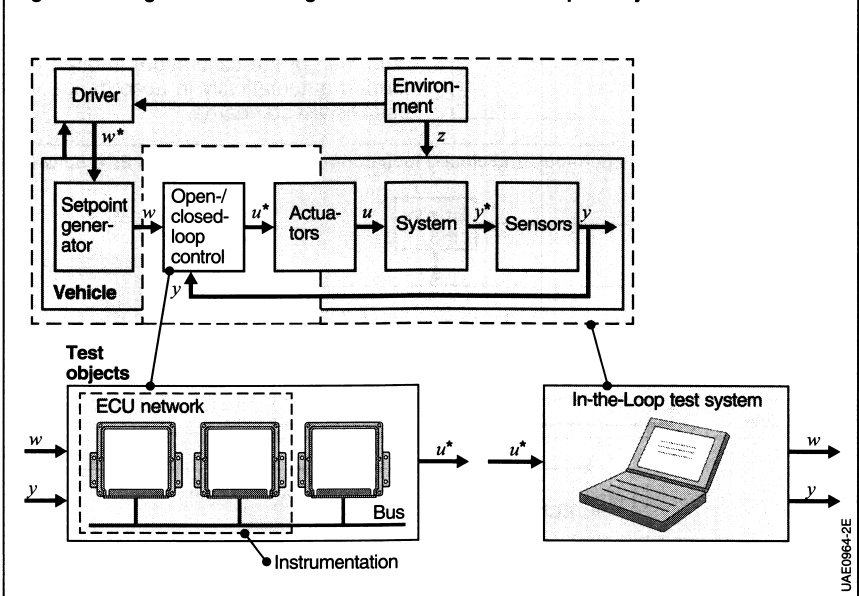
environment in the absence of actual peripheral components (Figure 12).

This allows tests to be performed and automated under reproducible laboratory conditions with a high level of flexibility. In contrast to tests on the test bench or in the real vehicle, the full, unrestricted range of operating states can be tested (for example, an engine ECU can be tested at all load and rpm situations). Vehicle wear and failure situations are easy to simulate, and allow testing of the monitoring, diagnostic, and safety functions of the ECU. Component tolerances (for example, in setpoint generators, sensors, and actuators) can be simulated to allow a verification of the robustness of open-loop and closed-loop control functions.

A significant benefit is also the great test depth which can be achieved through automation. This enables, for example, as many fault types as possible and their combinations to be tested under exactly reproducible conditions and documented by means of a failure log.

This procedure can also be applied to testing actual setpoint generators, sensors, and actuators. The interfaces of the

Figure 12: Integration and testing of ECUs with an In-the-Loop test system



test system need to be modified accordingly. Any intermediate steps can also be incorporated into the procedure.

A structure as illustrated in Figure 12 depicts the ECUs in the form of a black box. The behavior of the ECU functions can only be assessed on the basis of the input and output signals w , y and u^* . This “black-box view” is sufficient for simple software functions. But testing more complicated functions requires the integration of a measurement procedure for internal ECU intermediate variables. This type of measuring technique is also known as instrumentation. The testing of diagnostic functions also requires access to the fault memory via the ECU diagnostics interface, and this requires the integration of a measurement and diagnostics system.

In-the-Loop test systems

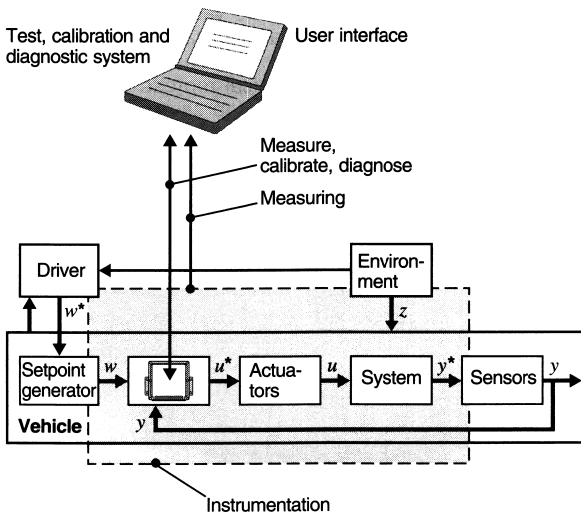
In-the-Loop is a test procedure in which an embedded electronic system is connected via interfaces to a real (e.g. sensors, actuators) or virtual environment (mathematical models). The reaction of the system is analyzed and played back to

the system. Depending on the type of test specimens, a distinction is made between the following test systems:

- In the case of Model-in-the-Loop (MiL), the function model of the software is tested. The model runs on a development computer.
- In the case of Software-in-the-Loop (SiL) the software code is tested. It runs on a development computer.
- In the case of Function-in-the-Loop (FiL), the software code is also tested. However, in contrast to SiL, this runs on the destination hardware. Coupling between the software and the environment model is performed by means of hooks and an emulator probe.
- In the case of Hardware-in-the-Loop (HiL), the complete ECU is tested by means of the input and output interfaces (I/O). Combinations of FiL and HiL are also used. PCs are increasingly being used as simulation computers.

In-the-Loop test systems can be used to validate and further develop software and hardware.

Figure 13: Integration and testing of ECUs in the real vehicle



Calibration of software functions

Procedure

Each electronically controlled vehicle system can only then develop its capability when it is optimally adapted to the respective vehicle type. In order for software functions to be used in as many vehicle variants as possible, these contain variable parameters. Adapting these parameters to the corresponding vehicle variant and for every operating condition (e.g. cold running, extreme heat or altitude) is known as calibration. To reach the desired level of functionality in the complete vehicle, a multitude of characteristic values, characteristic curves and program maps – the calibration data – must be applied.

Most changes to the vehicle require a change to the calibration. An example here: The λ oxygen sensor in the exhaust-gas system measures the residual oxygen in the exhaust gas. The fuel quantity actually injected can be determined on the basis of this signal. In this way, it is possible to adapt the activation parameters in the engine ECU exactly on a continuous basis. Changes to the exhaust-gas system which result in a change to the exhaust-gas back pressure at the point where the λ sensor is installed (e.g. altered exhaust manifold, particulate filter) must be adapted. If this is not done, this will result in a deterioration in consumption and emissions.

Variant management can be simplified in development, production and service by separating program and data statuses. The program status contains, for example, all the information on the variables to be applied and their limit values and correlations, while the data status contains the variables actually applied.

Calibration takes place in the laboratory on engine and vehicle test benches during vehicle tests and under real environmental conditions on test tracks. In addition to a measurement and diagnostic system, a calibration system is often required to calibrate internal ECU parameters (such as characteristic curves and program maps). On completion of calibration, the determined data are comprehensively checked. These values are then stored in the read-only memory (EPROM or flash) of the series ECU.

The parameter values must be variable during calibration. A calibration system, therefore, consists of one or more ECUs with a suitable interface to a measurement and calibration tool (Figure 14). In addition to their deployment in vehicles, measurement, calibration and diagnostic systems can also be used in in-the-loop test systems and on test benches. It is being applied more and more often in a virtual environment. Here, high-performance tools assist in finding the trade-off (optimal compromise of the calibration data).

Changes to the parameter values, for instance to the values of a characteristic curve, are supported in the calibration tool by editors. Alternatively, these operate on the implementation level (i.e. with the applied values) or on the physical specification level. Accordingly, the measurement tool converts recorded values into a physical representation or an implementation representation. Figure 14 shows an example of the physical and the implementation levels for a characteristic curve and a recorded measurement signal.

When working with calibration systems, it is usually possible to choose between offline and online calibration.

Offline calibration

In offline calibration, the execution of open-loop control, closed-loop control, and monitoring functions, i.e. of the “drive program”, are interrupted to modify or adjust parameter values. Offline application therefore leads to many restrictions. In particular when deployed on test benches and during in-vehicle testing, it always causes an interruption to the test-bench or road test.

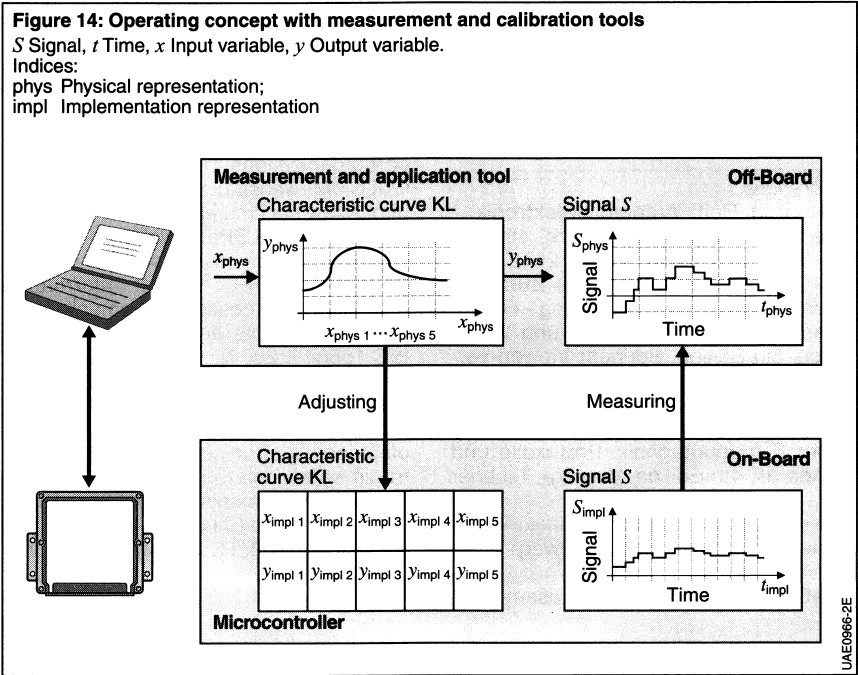
Online calibration

In online calibration, the parameter values can be adjusted while the microcontrollers are executing the software functions. It is, therefore, possible to adjust parameter values while executing open-loop control, closed-loop control, and monitoring functions at the same time, and hence during regular use at the test bench or in vehicle.

Online calibration places higher demands on the stability of the open-loop control, closed-loop control, and monitoring functions, since the driving schedule must remain stable during all adjustment

procedures if exceptions occur, for example, if the distribution of interpolation points in characteristic curves fails to rise monotonically for short periods of time. Online calibration is suitable for long-term modification of less dynamic parameters (for example, tuning of engine control functions on the engine test bench).

For applying more dynamic functions or safety-critical functions (for example, setting the software functions of an ABS system for braking maneuvers during a test drive), the settings are not adjusted during actual braking maneuvers. In this case, online calibration can still save time by avoiding any interruptions in the program execution, thus reducing the interval between two test drives.



Outlook

New vehicle functions and technologies will continue to lead to an increase in the scope of software in motor vehicles – even in the low price segment. In the process, the number of ECUs stays the same in many vehicles. As a consequence, the scope of functions of some ECUs is continuing to increase. In all, the system limits between the different ECUs are disappearing more and more, such as, for example, in the management of a hybrid drive. The electronics in motor vehicles are thus becoming ever more complex – including beyond an individual vehicle. The economic mastery of complexity is therefore certainly a key element in future automotive software engineering and the associated development environments.

Another trend is the increasing virtualization of development. Virtualization involves integrating parts of later development steps, such as testing and calibration, into the earlier development phases such that the function models can be optimally tested in-the-loop and fed with data on a preliminary basis early on. In this way, failures are detected earlier, support is provided for distributed development and bottlenecks shortly before series startup are avoided.

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Automotive networking

Bus systems

Networks for data communication, also known as bus systems or protocols, are widely used in today's motor vehicles. Various components such as sensors, actuators or ECUs – the “nodes” – are connected to each other via a single channel (Figure 1). A wealth of data, also known as messages, telegrams, packets or frames, is exchanged via this channel. For example, the driving speed is determined in the Electronic Stability Program (ESC) and transferred to all the other ECUs which are networked as nodes in the bus system.

Advantages of bus systems

Compared with conventional cabling, in which the transmitter and receiver of information are each connected by separate lines, bus systems offer significant advantages:

- The costs of materials for the cables are lower (which offsets the higher costs for the electronics).
- The space required and the weight of the cabling are lower.
- The number of plugs susceptible to faults is lower, thus fewer failures occur in total.
- Data can be distributed to various receivers; for example, the signals of a sensor can be used by several systems.

- All the systems in the vehicle which are connected via the bus can be reached from one access point. This provides for simpler diagnostics and the configuration of all the ECUs at the end of the line.
- The performance of calculations can be distributed to different ECUs.
- Analog sensor signals must be digitized for data processing. The sensor signals can be conditioned directly in the sensor, the information is then disseminated via the bus.

Requirements of buses

General requirements

In order to be able to be used in vehicles, buses must satisfy typical requirements. A bus must use a transmission process which has control over the propagation times, attenuations and reflections of the signals for cables up to 40 m long with which typically all the parts of the vehicle are reached. A network must be able to connect several dozen users in the process.

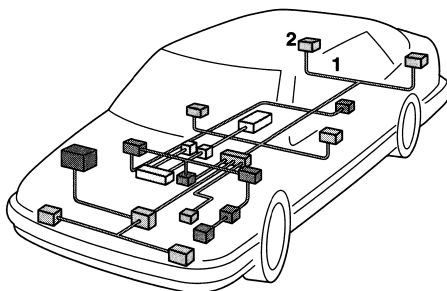
A bus must be able to withstand the rough ambient conditions in the vehicle with regard to temperature, vibrations and electromagnetic interference.

Because vehicles are produced in high numbers, even small savings potentials in the cost of the bus hardware of the individual vehicle must be utilized in the design of the bus. It is equally necessary for there to be several competing manufacturers of bus components.

Figure 1: Automotive networking

Schematic representation of nodes and data lines.

- 1 Data line,
2 Node (network user).



There is a large number of equipment variants of a vehicle type which must be covered by a basic configuration of the bus. The additional installation of an optional extra must not affect the other vehicle systems.

The performance of the bus must be clearly defined in a public standard in order to have a benchmark against which components can be verified. This ensures that verified components of different suppliers function together in a single network.

Special requirements

Different systems in the motor vehicle have different requirements and therefore necessitate the use of different buses. The required data transfer rate very much depends on the application. It ranges from a few bit/s for switching the lights, through engine management with a few 100 kbit/s, right through to video applications with several Mbit/s.

For systems in which a failure or a delayed execution of a function is safety-relevant (e.g. airbag, electric power steering), a maximum duration for data transfer (latency) must be guaranteed in all cases. When the time response of the bus is defined and reproducible at all times, this is referred to as determinism. In this way, transfer times for messages, in particular, are already known in the design phase.

For safety systems such as electric power steering it must be verified that everything has been done in terms of state-of-the-art technology to avoid flaws/faults in design and to ensure correct functioning under all permissible boundary conditions.

Transfer malfunctions which inevitably occur during operation must be detected and dealt with for the relevant application.

Technical principles

Components of a bus

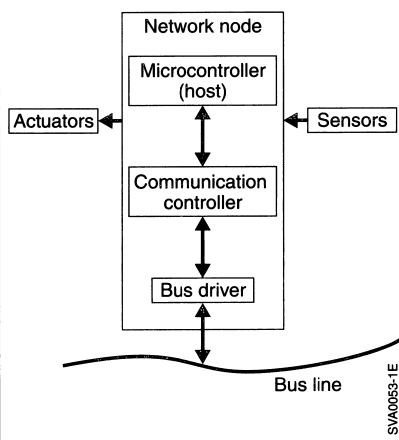
In order for a network to function as planned, calculations must be carried out constantly in every network user. This is performed for the most part by a special piece of hardware (Figure 2), the "communication controller". This removes the load from the actual computer (host), which can also perform this function – although less efficiently. The communication controller can be implemented as a separate semiconductor component; in the case of many microcontrollers, however, communication controllers for some buses are already integrated.

A further component, the bus driver or transceiver, converts the signal which it receives from the communication controller into the physical signal on the bus line (e.g. voltage level). It converts data received on the bus line and forwards them to the communication controller.

OSI reference model

The ISO (International Standardization Organization) developed the OSI reference model (Open Systems Interconnection), which is often used as the basis for describing and comparing communications protocols. In this model, the function of a data-communication system is

Figure 2: Hardware of a network user



broken down into different hierarchical layers which each use the functions made available by a different layer. The OSI reference model is an aid to structuring conceptually the function of a communication system. However, finding efficient solutions is not necessarily supported by observing this model.

Seven layers are defined (Figure 3), but many protocols are only defined on one part thereof. The upper layers in the OSI reference model (application layer, presentation layer and session layer) are for the most part not served by motor-vehicle buses.

Physical layer

The physical layer defines the physical properties of the transmission medium (e.g. voltage level or shape of plugs). In motor vehicles for the most part, electromagnetic signals in the kHz to MHz range are used on special cables and optical fibers. Radio of different frequencies or the joint use of cables already provided with electrical power for supply purposes are technologies which have not yet been tested in large batches.

The most widely used method is, because of the low costs involved, transmission by cable, particularly as a voltage difference on twisted two-wire cables, with or without shielding against radiation, or on single-wire cables with a voltage reference to ground.

Optical fibers made from plastic or glass fibers (for the infrared spectral range) are used above all wherever high data rates are needed. They are insensitive to electromagnetic radiation (e.g. by the ignition system), but are costly to lay and their resistance to aging has not yet been adequately assured.

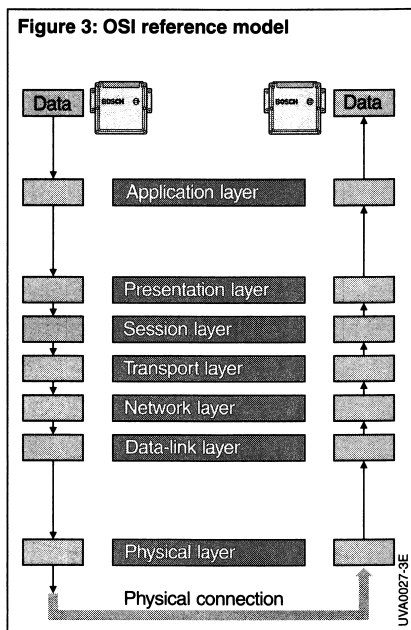
The physical possibilities of the medium also limit the types of encoding of a bit. With optical media, there are the two states "light" and "no light", which offer encoding by means of amplitude (brightness).

High-frequency electrical voltage signals on a cable offer different possibilities for representing bits. The simplest and usual method used in motor-vehicle buses is encoding in which each bit is assigned a voltage value (amplitude modulation) which is applied for the entire bit duration (NRZ, Non Return to Zero). In this frequency range, open cable ends must, if necessary, be terminated by terminating resistors in order to prevent reflections from disrupting the signal shape.

Data-link layer

The data-link layer effects the correct transport of data between neighboring nodes. Data bits are arranged into frames. By adding further bits such as checksums or numberings, it is possible to detect or even correct errors that occur during transfer. Alternatively, an error can be rectified by requesting a new transfer.

Figure 3: OSI reference model



Network layer

If not every network user is directly connected with every other, a route must be found for the data which passes through intermediate stations. The search for a route is also called routing and includes different characteristics of the transmission paths (particularly bandwidth) and the intermediate stations, also called routers.

Transport layer

The transport layer's functions include disassembling large data packets and reassembling them at the receiver, which the parts potentially reach via different routes at different times, or if transmission errors occur ensuring that a packet is transmitted again. The transport layer also serves to hide the properties of the transmission path from the application and to offer services independently.

Access methods

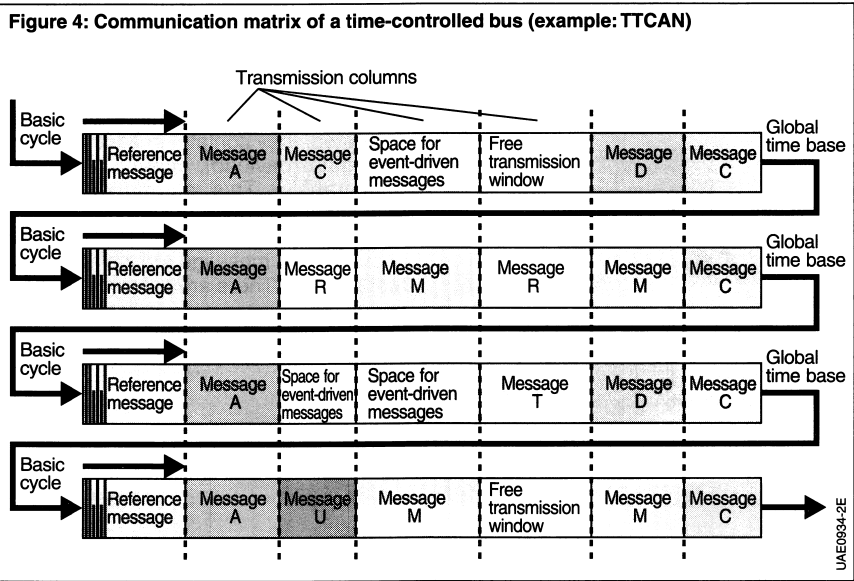
Data are usually transmitted as fixed-structure packets (frames), which, as well as the actual content, also contain control and test data such as source, destination, priority and check bits to protect against corruption.

A central function of a network to which several users have access at the same time is the administration of the token in order to avoid conflicts. This is known in buses as arbitration. It should be borne in mind here how urgently a message has to be transported. Different mechanisms are circulated.

Time control

With time-controlled buses, conflict-free access is possible whereby each node receives permanently allocated times (slots, columns) for its emissions. These recurring times are combined into cycles, and cycles combined into communication matrices (Figure 4).

The messages (reference messages, Sync Frame) themselves are used to synchronize the clocks in the nodes. If there are numerous timing nodes (time master) in the network, the clocks are synchronized on the basis of the measured

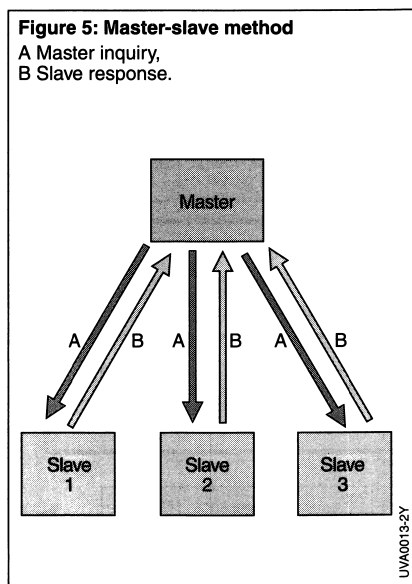


reception times with the expected reception times. The strict periodicity (determinism) makes it possible to quickly detect when a message fails to materialize, which is required particularly in safety systems such as electric-motor-operated steering.

In addition, the time-controlled approach promotes the possibility that several subsystems are developed independently of each other, because in this way the composability of the subsystems into predictable behavior of the overall system is supported. When each subsystem has its independent time slice, two nodes cannot disrupt each other by simultaneously occupying the bus.

Master-slave

A designated node (master) grants one of the other nodes (slave) limited access (Figure 5). In this way, it determines the communication frequency by interrogating its subordinate nodes. A slave responds only when it is addressed by the master. However, some master-slave protocols permit a slave to register with the master in order to send a message.



Multi-master

In a multi-master network, various nodes can access the bus automatically and send a message if the bus appears free. In other words, each node can perform the master role and all the nodes can equally start a message transfer. However, this also means that methods for identifying and dealing with access conflicts must be in place. This can be done, for example, by way of a decision phase with prioritization or a delayed resending. The use of priority control prevents a bus conflict when several nodes want to occupy the bus at the same time. The network node which has a high priority or which would like to transmit a high-priority message asserts itself and sends its message first. When the line is free again, all the nodes which have to send messages – particularly the node that is waiting – start with a renewed attempt.

The multi-master architecture has a positive effect on system availability because communication is not controlled by any single node, the failure of which would result in a total communication failure.

Token passing

The right of access is temporarily awarded to a node, which then passes it on to another node for a limited time.

Addressing

In order for messages to be transferred via a network and their information to be evaluated, they contain, in addition to the user data (payload), information on the data transfer. This information can be contained explicitly in the transfer or stipulated implicitly. Addressing is required to ensure that a message arrives at the correct receiver. There are different methods of doing this.

User-oriented method

Data are exchanged here on the basis of node addresses (Figure 6a). The message transmitted by the sender contains, as well as the data to be transferred, the address of the destination node. All the receivers compare the transmitted receiver address with their own and only those receivers with the correct address evaluate the message. Messages can be directed to individual addressees, to groups (multicast) or to all the nodes in the network (broadcast).

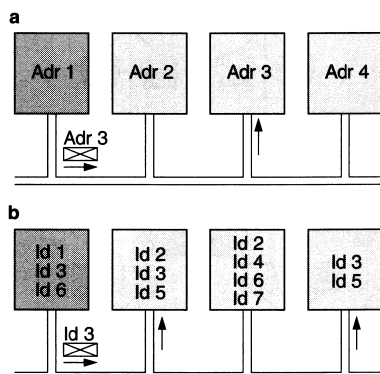
Most conventional communication systems (e.g. Ethernet) operate in accordance with the principle of user addressing.

Message-oriented method

With this method, it is not the receiver nodes but the messages themselves which are addressed (Figure 6b). A message is identified according to its content by a message identifier which was established in advance for this information type. With this method, the sender does not require any knowledge of the destination of the message, since each receiver node decides for itself whether to process the message. Several nodes can also accept and evaluate the message.

Figure 6: Addressing types

- a) User-oriented method,
b) Message-oriented method.
Adr i , $i = 1 \dots n$, address of nodes.
Id i , $i = 1 \dots n$, message identifiers.



Most bus systems in the automotive field (e.g. CAN, FlexRay) operated according to the message-oriented method.

Transfer-oriented method

Even transfer features can be used to identify a message. If a message is always sent in a defined time slot, it can be identified using this item. For safeguarding purposes, this addressing is also combined in many cases with a message- or user-oriented addressing.

Network topology

A network topology refers to the structure of network nodes and connections. This shows which nodes are connected to each other, but not the details, such as the length of the connection for example. For different applications of communication networks, there are different requirements of the topology used.

Bus topology

This network topology is also referred to as a linear bus. The core element is a single cable, to which all the nodes are connected by way of short connecting cables (Figure 7a). In this topology, it is very easy to expand the network by additional users. Messages are sent out from the individual bus users and distributed to the entire bus.

If a node fails, the data expected from this node are not available to the other nodes in the network, but the remaining nodes can continue to exchange messages. However, a network with a bus topology will fail completely if the central cable has a fault (e.g. in the event of a cable break).

Star topology

The star topology consists of a central node (repeater, hub, star), to which all the other nodes are connected by way of individual connections (Figure 7b). A network with this topology can therefore be easily expanded if free connections are available at the central element.

Data are exchanged via the individual node connections with the central star, where a distinction is made between active and passive stars. The active star contains a computer which processes and forwards the data. The network's perfor-

mance is significantly determined by the performance of this computer. The central node, however, does not necessarily have to have special control intelligence. A passive star only joins the bus lines of the network users.

If one network user fails or a connecting cable to the central node is faulty, the remaining network continues to be operational. If, on the other hand, the central node fails, then the entire network is rendered inoperational.

Ring topology

In the ring topology, each node is connected to its two neighbors. This creates a closed ring (Figure 7c). In a ring, data are transferred in only one direction from one station to the next. The data are checked in each case after they are received. If they are not intended for this station, they are renewed (repeater function), amplified, and sent forward to the next station. The data to be transferred are forwarded in the ring, i.e. from one station to the next, until they reach their intended destination or arrive at the starting point again. When a message has passed through the complete ring, reception is acknowledged by all the nodes. Once one station in a single ring fails, data transfer is interrupted and the network fails completely.

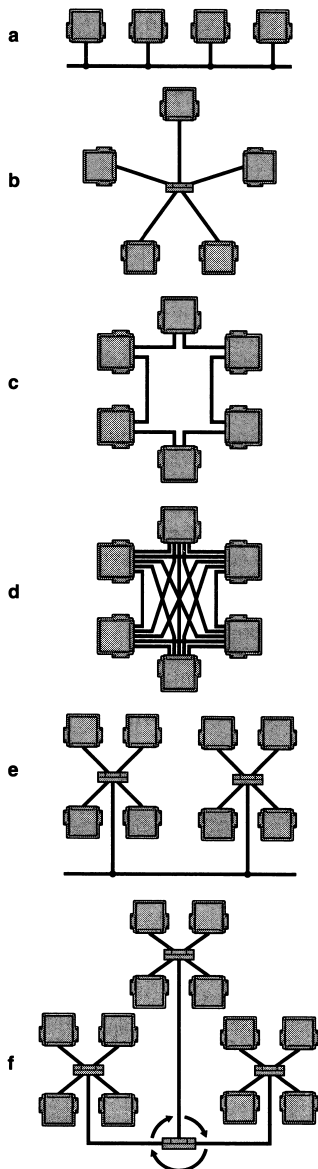
Rings can also be structured in the shape of a double ring in which data are transferred in both directions. In this topology, the failure of one station or of a connection between two stations can be managed, since all the data continue to be transferred to all the operational stations in the ring.

Daisy-chain topology

The daisy-chain topology looks like the ring topology when a connection is removed. Here, the first component is connected directly to data-processing equipment (e.g. a computer). The subsequent components are connected to their preceding components (series-connection principle), thereby creating a chain. Messages thus pass through several nodes until the destination is reached.

Figure 7: Network topologies

- a) Bus topology, b) Star topology, c) Ring topology, d) Mesh topology, e) Star-bus topology, f) Star-ring topology.



Mesh topology

In a mesh topology, each node is connected to one or more further nodes (Figure 7d). In the event of the failure of a node or a connection, there are diversions along which the data can be routed. This network is therefore characterized by high failure tolerance. However, the costs of networking and transporting the messages are high.

Hybrid topologies

In hybrid topologies, different network topologies are connected. The following combinations are possible, for example:

- Star-bus topology: The hubs of various star networks are connected to each other as a linear bus (Figure 7e).
- Star-ring topology: The hubs of various star networks are connected to the main hub (Figure 7f). In this main hub, the hubs of the star networks are connected in a ring shape.

Transfer reliability

An important feature of buses, particularly if they are to be used in safety-relevant systems, is their ability to identify faults and, if necessary, to maintain limited operation. This includes the possibility of detecting the corruption of data. Electromagnetic radiation from the surroundings (e.g. from the ignition coil) on the cables may cause some bits to assume incorrect values at the receiver. These incidents can be identified by transferring check information in addition to the data. The simplest case is an additional parity bit, which is used to detect whether the correct number of ones is even or uneven. A generalization of this is the “Cyclic Redundancy Check” (CRC), with which different qualities of protection can be obtained using a selectable number of check bits.

One way of ensuring limited operation is to bypass failed lines and prevent blockage of the bus by faulty nodes.

It is ensured that an item of data sent out by a node, e.g. the vehicle speed, is available either to all the addressees in the network or to none (consistency). The situation where two nodes have different images of the speed value therefore cannot arise. For this purpose, a node signals that reception has failed or refrains from acknowledging correct reception (acknowledge). The other nodes then reject the data already correctly received by them.

Buses in motor vehicles

External buses connect ECUs, sensors, and actuators to each other. They run via a wiring harness and plug-in connections. Levels, bit rates, and impedances are precisely defined in order to ensure interoperability. Examples are CAN, FlexRay, and LIN. For a quick overview, these buses are frequently classified according to the scheme in Table 1.

Internal buses connect integrated circuits on the board. They are only used inside an ECU.

Table 1: Classification of bus systems

Class A	
Data transfer rates	Low data rates (up to 10 kbit/s)
Applications	Networking of actuators and sensors
Represented by	LIN, PSI5
Class B	
Data transfer rates	Medium data rates (up to 125 kbit/s)
Applications	Complex mechanisms for error handling Networking of control units in the comfort area
Represented by	Lowspeed-CAN (CAN-B)
Class C	
Data transfer rates	High data rates (up to 1 Mbit/s)
Applications	Real-time requirements Networking of control units in the drive and chassis area
Represented by	High-speed CAN (CAN-C)
Class C+	
Data transfer rates	Very high data rates (up to 10 Mbit/s)
Applications	Real-time requirements Networking of control units in the drive and chassis area
Represented by	FlexRay
Class D	
Data transfer rates	Very high data rates (from 10 Mbit/s)
Applications	Networking of control units in the areas of telematics and multimedia
Represented by	MOST, Ethernet

CAN

Overview

The CAN bus (Controller Area Network) has established itself as the standard since its first series introduction in motor vehicles in 1991. But it is also often used in automation technology. The major features are:

- Priority-controlled message transmission with non-destructive arbitration.
- Low costs through the use of a low-cost twisted two-wire cable and use of a simple protocol with low computing-power demand.
- A data-transfer rate up to 1 Mbit/s for the high-speed CAN (CAN-C) and up to 125 kbit/s for the low-speed CAN (CAN-B, lower expenditure for the hardware).
- High reliability of data transfer through recognition and signaling of sporadic faults and permanent faults and through network-wide consistency via Acknowledge.
- The multi-master principle.
- High availability by locating failed stations.
- Standardization in accordance with ISO 11898 [1].

Transfer system

Logic bus states and encoding

To communicate, the CAN bus uses the two states “dominant” and “recessive”, with which the information bits are transmitted. The dominant state represents “0”, the recessive “1”. The NRZ process (Non Return to Zero) is used as encoding for transmission, in which a zero state is not always returned to between two equal transfer states and, therefore, the time interval between two edges which is required for synchronization can become too great.

For the most part a two-wire cable with, depending on the ambient conditions, a non-twisted or twisted pair is used. The two bus lines are called CAN_H and CAN_L (Figure 1).

The two-wire cable facilitates a symmetrical data transfer, in which the bits are transferred via both bus lines using different voltages. This reduces sensitivity to common-mode interference, since interference affects both lines and can be filtered out by creating the difference (Figure 2).

The single-wire cable represents a way of lowering manufacturing costs by saving on the second cable. However, a common ground connection which assumes the function of the second cable must be available to all the bus users for this purpose. The single-wire version of the CAN bus is therefore only possible for a communication system with limited spatial reach. Data transfer on the single-wire cable is more susceptible to interference radiation, since it is not possible to filter out interference pulses as on the two-wire cable. A higher level signal on the bus line is therefore required. This in turn has a negative effect on the interference radiation. The edge steepness of the bus signals must therefore be reduced compared with the two-wire cable. This is associated with a lower data-transfer rate. For this reason, the single-wire cable is

only used for the low-speed CAN in the area of body and comfort and convenience electronics. The single-wire solution is not described in the CAN specification.

There are also so-called fault tolerant transceivers, which communicate via a two-wire cable, but if a cable breaks continue operating as a single-wire system.

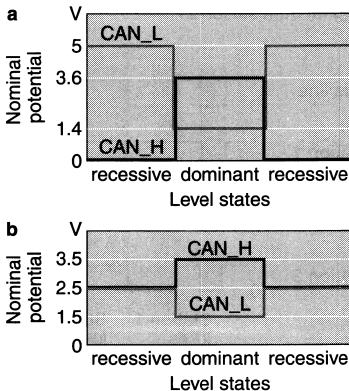
Voltage levels

High-speed and low-speed CANs use different voltage levels to transfer dominant and recessive states. The voltage levels of the low-speed CAN are shown in Figure 1a, those of the high-speed CAN in Figure 1b.

The high-speed CAN uses, in the recessive state on both lines, a nominal voltage of 2.5 V. In the dominant state, nominal voltages of 3.5 V and 1.5 V are applied to CAN_H and CAN_L respectively. In the low-speed CAN in the recessive state, a voltage of 0 V (max. 0.3 V) is applied to CAN_H and a voltage of 5 V (min. 4.7 V) is applied to CAN_L. In the dominant state, the voltage at CAN_H is min. 3.6 V and at CAN_L max. 1.4 V.

Figure 1: Voltage level of CAN data transfer

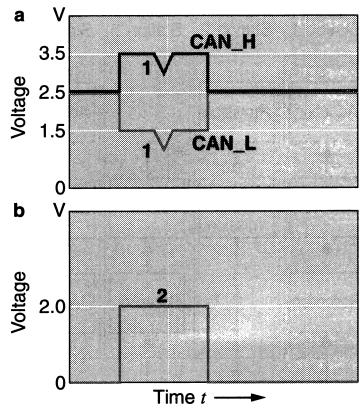
- a) Low-speed CAN (CAN-B),
b) High-speed-CAN (CAN-C).
CAN_H CAN High level,
CAN_L CAN Low level.



SVC0018-2E

Figure 2: Filtering out of interference on the CAN bus

- a) Signal level of CAN lines with interference on both lines,
b) Difference signal.
1 Interference pulse,
2 Difference signal.
CAN_H CAN High level,
CAN_L CAN Low level.



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Limits

It is important for the arbitration method in the case of CAN that all the nodes in the network see the bits of the message identification (frame identifier) simultaneously so that a node – while it is still transmitting a bit – sees whether another node is also transmitting. Delays result from the signal propagation time on the data bus and the processing times in the transceiver. The maximum permissible transfer rate is thus dependent on the overall length of the bus. ISO specifies 1 Mbit/s for 40 m. For longer lines, the possible transfer rate is roughly inversely proportional to the line length. Networks with a 1 km reach can be operated with 40 kbit/s.

CAN protocol

Bus configuration

CAN operates according to the multi-master principle, in which a linear bus topology connects several nodes of equal priority rating.

Content-based addressing

CAN uses message-based addressing. This involves assigning a fixed identifier to each message. The identifier (ID) classifies the content of the message (e.g. engine speed). Each station processes only messages whose identifiers are stored in the list of messages to be accepted. This is called acceptance checking (Figure 3). Thus, the CAN requires no station addresses for data transmission, and the nodes are not involved in managing the system configuration. This facilitates adaptation to variations in equipment levels.

Logic bus states

The CAN protocol is based on two logic states: The bits are either “recessive” (logic 1) or “dominant” (logic 0). When at least one station transmits a dominant bit, it overwrites the recessive bits simultaneously sent by other stations.

Bus arbitration and priority assignments

Each station can begin transmitting a message as soon as the bus is unoccupied. When several stations start to transmit simultaneously, a “wired-and arbitration scheme” becomes active to resolve the resulting bus-access conflicts. The arbitration scheme ensures that the domi-

Figure 3: Addressing and acceptance checking

Station 2 sends, stations 1 and 4 receive the data.

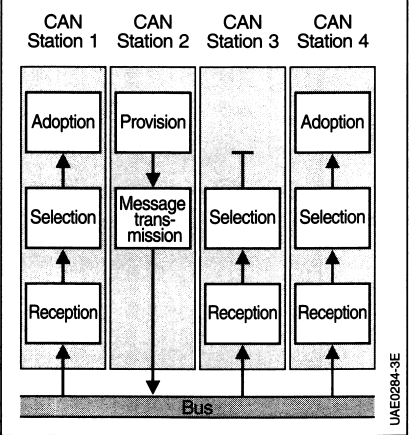
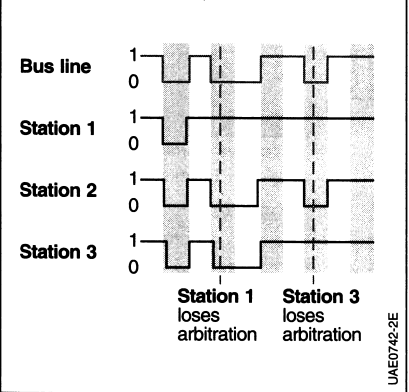


Figure 4: Bitwise arbitration

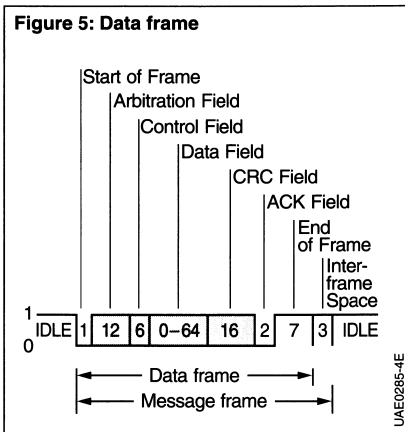
0 Dominant level,
1 Recessive level.
Station 2 gains first access
(signal on the bus corresponds
to signal from station 2).



nant bits transmitted by a station overwrite the recessive bits of other stations (Figure 4). Each station gives bit by bit – the highest significant bit first – the identifier of its message on the bus. During this arbitration phase (selection phase) each transmitting station compares the applied bus level with the actual level. Each station that transmits a recessive bit but observes a dominant bit loses arbitration. The station with the lowest identifier – i.e. with the highest priority – is assigned first access on the bus without having to repeat the message (non-destructive access control). Transmitters respond to failure to gain bus access by automatically switching to receive mode; they then repeat the transmission attempt as soon as the bus is free again.

Data frame and message format

The CAN supports two different message formats, which primarily differ with respect to the length of their identifiers. The standard format has 11 bits, while the extended format has 29 bits. Thus, the data frame to be transmitted contains a maximum of 130 bits (in the standard format) and 150 bits (in the extended format). This ensures minimum waiting time until the next transmission (which could be urgent). The data frame for the standard format consists of seven consecutive fields (Figure 5). The "Start of Frame" indicates the beginning of a message and synchronizes all nodes.



The "Arbitration Field" consists of the message's identifier and an additional control bit. While this field is being transmitted, the transmitter accompanies the transmission of each bit with a check to ensure that no higher-priority message is being transmitted (which would cancel the access authorization). The control bit determines whether the message is classified under "data frame" or "remote frame".

The "Control Field" contains the code indicating the number of data bytes in the "Data Field".

The "Data Field" has an information content of between 0 and 8 bytes. A message of data length 0 can be used to synchronize distributed processes.

The "CRC Field" (Cyclic Redundancy Check) contains a checksum for detecting possible transmission interference.

The "Ack Field" contains the acknowledgement signals with which the receivers indicate the error-free receipt of messages.

The "End of Frame" marks the end of the message.

Then comes the "Interframe Space" to provide a separation from the next data frame.

Transmitter initiative

The transmitter will usually initiate a data transmission by sending a data frame. However, the receiver can also request data from the transmitter. This involves the receiver sending off a "Remote Frame". The "Data Frame" and the corresponding "Remote Frame" have the same identifier. They are distinguished by the bit that follows the identifier.

Error detection

The CAN incorporates a number of monitoring features for detecting errors. These include:

- 15-bit CRC: Each receiver compares the CRC sequence which it receives with the calculated sequence.
- Monitoring: Each transmitter reads its own transmitted message from the bus and compares each transmitted and scanned bit.
- Bit stuffing: Between "Start of Frame" and the end of the "CRC Field", each "Data Frame" or "Remote Frame" may contain a maximum of five consecutive bits of the same polarity. The transmitter follows up a sequence of five bits of the same polarity by inserting a bit of the opposite polarity in the bitstream. The receivers eliminate these bits again as the messages arrive.
- Frame check: The CAN protocol contains several bit fields with a fixed format for verification by all stations.

Error handling

When a CAN controller detects an error, it aborts the current transmission by sending an error flag. An error flag consists of six dominant bits; it functions by deliberately violating the stuffing convention and the formats.

Fault confinement with local failure

Defective stations can severely impair the ability to process bus traffic. Therefore, the CAN controllers incorporate mechanisms which can distinguish between intermittent and permanent errors, and local station failures. This process is based on statistical evaluation of error conditions.

Implementations

The semiconductor manufacturers offer different implementations of CAN controllers which differ primarily in the extent to which they can store and manage messages. In this way, the host computer can be relieved of protocol-specific activities. A standard categorization is Basic CAN controllers, which have only a few message memories, and Full CAN controllers, in which there is room for all the messages necessary for an ECU.

Standardization

The CAN has been standardized for data exchange in motor vehicles; for applications with a low transfer rate up to 125 kbit/s as ISO 11898-3 [1] and for applications with a high transfer rate over 125 kbit/s as ISO 11898-2 [1] and SAE J 1939 (truck and bus, [2]).

Time-triggered CAN

The extension of the CAN protocol to include the capability of operating in time-triggered mode is called "Time-Triggered CAN" (TTCAN). It is fully configurable with regard to the proportion of time-triggered to event-driven communication components, and is therefore fully compatible with CAN networks. TTCAN is standardized as ISO 11898-4 [1].

CAN with flexible data rate

CAN-FD extends CAN by a second bit rate and a wider data field. Unlike the nominal bit rate previously applicable to CAN, the data bit rate is not limited to 1 Mbit/s. The data bit rate acts exclusively on the data field within the data frame, whereas the nominal bit rate still acts on the control data.

In addition, CAN-FD increases the data field from 8 to up to 64 bytes. This also necessitates adaptations to the checksum so as not to compromise transmission reliability. CAN-FD is standardized as ISO 11898-7 [1].

FlexRay

Overview

FlexRay is a bus which was designed for control engineering in the automotive field. Particular attention was given in development to its suitability for use in active safety systems without a mechanical fallback level (X-by-Wire), where determinism and fault tolerance are required. Essentially, thanks to the high transfer rate of up to 20 Mbit/s for non-redundant transmissions, its use in the field of audio transmission or for highly compressed video transmission is also conceivable. The major features are:

- Time-triggered transmission with guaranteed latency,
- Possibility of event-driven transmission of information with prioritization,
- Transmission of information via one or two channels,
- High transfer rate of up to 10 Mbit/s, with parallel transfer via two channels up to 20 Mbit/s,
- Structure as a linear bus, in a star configuration or as a mixed form.

FlexRay is the first automotive communication standard to have been created in a consortium of vehicle manufacturers, suppliers and semiconductor manufacturers. It contains elements from TTCAN, Byteflight and other technologies. The specifications published by the FlexRay

Consortium are today (only) available as ISO standard 17458 [3].

Transmission media

The transmission medium used in a FlexRay system is a twisted-pair two-wire cable where both shielded and non-shielded cables can be used. Each FlexRay channel consists of two strands, Bus-Plus (BP) and Bus-Minus (BM). FlexRay uses NRZ (Non Return to Zero) for encoding.

The bus state is identified by measuring the voltage difference between Bus-Plus and Bus-Minus. Data transfer is thus less sensitive to external electromagnetic influences, since these act equally on both strands and cancel each other out in the difference.

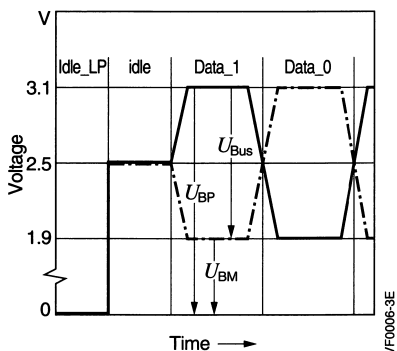
When different voltages are applied to the two strands of a channel, four bus states can be assumed; these bus states are referred to as Idle_LP (LP, Low Power), Idle, Data_0, and Data_1 (Figure 6). Idle_LP is the state in which a low voltage between -200 mV and 200 mV (to ground) is applied to Bus-Plus and Bus-Minus. In the Idle state, a voltage of 2.5 V with a maximum difference of 30 mV is applied to BP and BM. In order to place the channel in the Data_0 state, at least one transmitting node must apply a negative differential voltage of -600 mV to the channel, for Data_1, 600 mV, based on a mid-level of 2.5 mV.

Topologies

FlexRay networks can be structured as bus topologies and star topologies. Two stars can be cascaded – when signal delays are taken into consideration in the stars. Topologies in which several buses are connected to a star are also possible.

Because both channels of a FlexRay system can be structured independently of each other, it is possible for different topologies to be used for both channels. For example, one channel can be structured as an active star topology, the other as a bus topology.

Figure 6: Bus states and voltages for FlexRay



On account of the frequencies, which can be ten times those of CAN, it is necessary when designing a FlexRay network to ensure in all topologies in particular that parameters such as line length and terminating resistors are selected in such a way that signal distortions remain in the permissible range.

Bus access, time control

In order to achieve determinism, i.e. the guarantee of a maximum duration for the transmission of a message, communication is performed in the FlexRay bus on a time-controlled basis in cycles of constant duration. Each cycle first features a static segment which is divided into time slots of equal length (Figure 7). Each time slot is permanently assigned a maximum of one node which is permitted to transmit at this time.

This is followed by a dynamic segment in which bus access is regulated by the priority of messages. The split between the static and dynamic segments is freely configurable, but cannot be altered during operation. The same applies to the lengths of the time slots, which are configurable, but must remain constant during operation.

The “Symbol Window” can optionally be defined as the third element in the cycle. This can be used to transmit a single symbol. Symbols are provided to wake a network and to test functionalities.

Synchronization

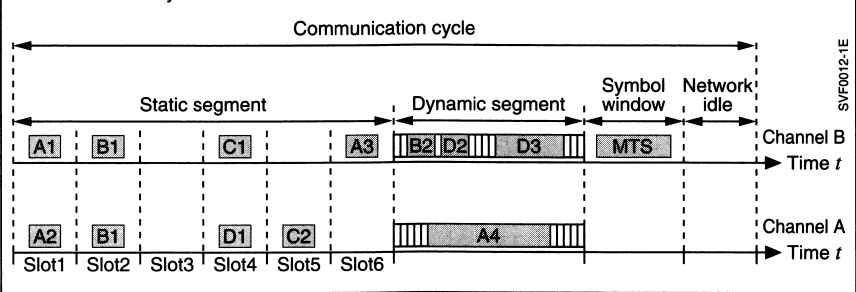
Each network node requires its own time generator, which it utilizes to decide the time for transmitting and to determine the duration of the bits. The internal time generators of several nodes may deviate from each other on account of temperature and voltage fluctuations and manufacturing tolerances. In a bus system such as FlexRay, which controls bus access via time slots, it is therefore necessary to ensure that the deviation of the clocks from one another remains within a permissible range through regular corrections. To this end, some nodes assume the role of time generators, to which the other nodes regularly synchronize their internal clocks. The procedure adapts both the zero points (offset) of the clocks and their rate. It can continue to operate even if individual nodes fail. To be able to make corrections, each cycle ends with a short phase (NIT, Network Idle Time) in which the zero point of the cycle can be shifted.

Thanks to this procedure a “global time” is provided in all the nodes; this time is given in microticks. The synchronization mechanism causes the length of one microtick to be the same on average in all the nodes.

When the network is switched on, a common conception of time on the part of all the nodes must first be established. The start-up process, which takes a little time, serves this purpose. Likewise, a node which intends to synchronize itself to a running network needs a period of time to be taken into consideration.

Figure 7: Time control for FlexRay (example)

A1 Node A transmits message 1,
A2 Node A transmits message 2,
MTS Media Test Symbol.



Arbitration in the dynamic segment

Messages can be given different priorities in the dynamic segment. The duration until a message is transmitted cannot be guaranteed for this. The priority is established by the frame ID, which may be allocated only once in the network. The messages are transmitted in the sequence of their frame ID. To this end, each node runs a counter (slot ID), which is increased when a message is received. If the slot ID assumes the value of the frame ID of a message ready in this node, it is transmitted. If the length of the dynamic segment is not sufficient for all the messages, the transmission process must be shifted to a later cycle.

The data frames in the dynamic segment can have different lengths. The limits of the dynamic slots on the two channels are independent of each other. Thus, there may be messages with different slot IDs on the channels at one time.

Data frame

FlexRay uses in both the static and dynamic segments the same data-frame format, which can be divided into the three sections of Header, Payload and Trailer (Figure 8).

Header

The header comprises:

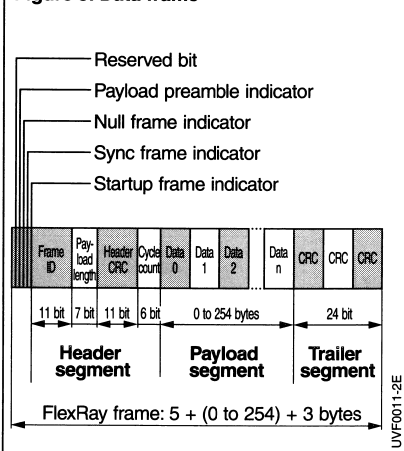
- The reserved bit for future protocol changes.
- The payload preamble indicator, which identifies whether the payload contains a network management vector.
- The null frame indicator, which identifies that the data have not been updated since the last cycle.
- The sync frame indicator, which signals that this data frame is to be used to synchronize the system.
- The startup frame indicator, which identifies that this frame is used in the network's start-up phase.
- The frame ID; this corresponds to the number of the slot in which the data frame is transmitted.
- The payload length which contains the size of the user data. For all the slots in the static segment this field always contains the same value. Data frames in the dynamic segment can have different lengths.
- The header CRC, which provides this part of the data frame with extra protection, because it is crucial to the time response.
- The cycle count; the number of the cycle in which the transmitting network node is located is transmitted in this field.

Payload

The user data which are processed further by the host are transmitted in the payload segment. For data frames in the static segment the first payload bytes can optionally be declared to the network management vector. The controllers or all the vectors received in the cycle and make them accessible to the host. For data frames in the dynamic segment the first payload bytes can optionally be declared to a 16-bit message ID. In both cases, subsequent handling is left to the software.

The user data have a maximum length of 254 bytes, which are transmitted in 2-byte words.

Figure 8: Data frame



Transfer system

The LIN bus is designed as a non-shielded single-wire cable. The bus level can assume two logic states. The dominant level corresponds to a voltage of approximately 0 V (ground) and represents logic 0. The recessive level corresponds to the battery voltage U_{batt} and represents the logic 1 state.

Because of the different design variations of the circuitry, the levels may be subject to differences. The definition of tolerances for transmitting and receiving in the field of the recessive and dominant levels ensures a stable data transfer. The tolerance bands are wider at the receiving end (Figure 9) so that valid signals can also be received in spite of interference radiation.

The transfer rate of the LIN bus is limited to 20 kbit/s. This is a compromise between the demand for high edge steepness to synchronize the slaves easily on the one hand and the demand for low edge steepness to improve EMC performance on the other. Recommended transfer rates are 2,400 bit/s, 9,600 bit/s and 19,200 Bit/s. The minimum permissible value for the transfer rate is 1 kbit/s.

The maximum number of nodes is not stipulated in the LIN specification. Theoretically, it is limited by the number of available content-related message identifiers. Line and node capacities and edge steepnesses limit the combination of length and node number of a LIN network; a maximum of 16 nodes is recommended.

The bus users are usually arranged in a linear bus topology; however, this topology is not explicitly prescribed.

Bus access

In the LIN bus, access is provided on the basis of the master-slave access method. The network features a master, which initiates each message. The slave has the opportunity to respond. The messages are exchanged between the master and one, several or all the slaves.

The following relationships are possible during communication between master and slave:

- Message with slave response: The master transmits a message to one or more slaves and asks for data (e.g. switch states of measured values).
- Message with master instruction: The master issues control instructions to a slave (e.g. switching on a servomotor).
- Message for initialization: The master initiates a communication between two slaves.

LIN protocol

Data frame

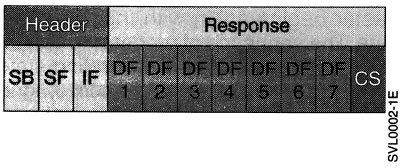
The information on the LIN bus is embedded in a defined data frame (LIN frame) (Figure 10). A message initiated by the master begins with a header. The message field (response) contains different information depending on the type of message. If the master transmits control instructions for a slave, it describes the message field with the data to be utilized by the slave. In the event of a data request, the addressed slave describes the message field with the data requested by the master.

Header

The header is made up of the synchronization break (Synch Break), the synchronization field (Synch Field), and the identifier field (Ident Field).

Figure 10: LIN frame

SB Synch Break,
SF Synch Field,
IF Ident Field,
DF Data Field,
CS Checksum.



Synchronization

A synchronization takes place at the start of each data frame to ensure a consistent data transfer between master and slaves. First the start of a data frame is clearly identified by the Synch Break. It consists of at least 13 consecutive dominant levels and one recessive level.

After the Synch Break, the master transmits the Synch Field, consisting of the bit sequence 01010101. The slaves thus have the opportunity to adapt themselves to the master's time base. The clock pulse of the master should not deviate from the nominal value by more than $\pm 0.5\%$. The clock pulse of the slaves may deviate prior to synchronization by up to $\pm 15\%$ if the synchronization achieves a deviation of max. $\pm 2\%$ up to the end of the message. The slaves can thus be designed without an expensive quartz oscillator, for example with a cost-effective RC circuit.

Identifier

The third byte in the header is used as the LIN identifier. Similarly to the CAN bus, content-based addressing is used – the identifier therefore gives information about the content of a message. All the nodes connected to the bus decide on the basis of this information whether they intend to receive and process the message or ignore it (acceptance filtering).

Six of the eight bits of the identifier field determine the identifier itself, from which 64 possible identifiers (ID) are obtained. They have the following meanings:

- ID = 0–59: Transmission of signals,
- ID = 60: Master request for commands and diagnostics,
- ID = 61: Slave response to ID 60,
- ID = 62: Reserved for manufacturer-specific communication,
- ID = 63: Reserved for future expansions of the protocol.

Of the 64 possible messages, 32 may contain only two data bytes, 16 four data bytes, and the remaining 16 eight data bytes.

The last two bits in the Ident Field contain two checksums, with which the identifier is protected against transmission errors and resulting incorrect message allocations.

Data field

Transmission of the actual data begins after the master node has transmitted the header. The slaves identify from the transmitted identifier whether they are addressed and, if necessary, transmit back the response in the data field.

Several signals can be packed into a data frame. Here, each signal has exactly one generator, i.e. it is always described by the same network node. During operation it is not permitted to change the signal allocation to another generator, as would be possible in other time-controlled networks.

The data in the slave response are safeguarded by a checksum (CS).

LIN description file

The configuration of the LIN bus, i.e. the specification of network users, signals and data frames, is performed in the LIN description file. The LIN specification provides for a suitable configuration language for this purpose.

From the LIN description file, tools automatically generate program sections which are used to implement the master and slave functions in the ECUs located on the bus. The LIN description file thus serves to configure the entire LIN network. It is a common interface between the vehicle manufacturer and the suppliers of the master and slave modules.

Message scheduling

The scheduling table in the LIN description file determines the order and time frame in which the messages are transmitted. Frequently needed information is transmitted from time to time. When the table has been worked through, the master begins again with the first message. The sequence of processing can be altered depending on the operating state (e.g. diagnostics active or inactive, ignition on or off).

Thus, the transmission frame of each message is known. The deterministic performance is guaranteed by the fact that all the transmissions are initiated by the master in the case of master-slave access control.

Network management

The nodes of a LIN network can be placed in sleep mode in order to minimize closed-circuit current. Sleep mode can be achieved in two ways. The master transmits the "Go to Sleep" command with the reserved identifier 60, or the slaves automatically go into sleep mode if there has been no data transfer on the bus for an extended period of time (four seconds). Both the master and the slaves can wake up the network again. The wake-up signal must be transmitted for this purpose. This consists of a data byte with the number 128 as content. After a break of 4 to 64 bit times (wake-up delimiter), all the nodes must be initialized and be able to respond to the master.

Ethernet

Overview

The term Ethernet refers to a family of buses in which the addressing, the format of the messages and access control are identical (laid down in IEEE 802, [5]). Ethernet and the Internet Protocol (IP) were developed for data communication between computers or peripherals which are locally separate and where, during operation, reconfigurations of the network through the addition of new users or the failure of users can occur. The Ethernet buses are identified by the following important features:

- The transfer rate is in the range of 10 Mbit/s up to 10 Gbit/s.
- Data transfer is possible via assorted media such as coaxial cable, twisted two-wire cable, radio or glass fiber.
- The technology involved is standardized and very widely used.
- Simple insertion and removal of nodes is possible.
- The time response in the case of real-time applications is not guaranteed.

Ethernet is used in series-production vehicles; e.g. in the BMW 7 Series, where it is used to input vehicle data at the end of production.

Transfer system

The Ethernet versions differ in terms of transfer rate, physical design of the channel, and encoding. Coaxial cables, twisted two-wire cables with one or more core pairs, optical fibers, radio paths, or even power-supply cables are specified as channels. Encoding differs accordingly.

Originally, coaxial cables in a bus topology were used as the medium. Here, the transceivers of the nodes were connected either directly or with T-pieces to the cable. Today, twisted two-wire cables are widely used. The transfer rates have been increased from initially 10 Mbit/s via the Fast Ethernet with 100 Mbit/s and the Gigabit Ethernet with 1,000 Mbit/s up to 10 Gbit/s.

Topology

The size of a network is limited by the fact that the signal propagation time between two nodes influences the arbitration process. This can be bypassed by subdividing into segments, which are connected by way of special components – hubs and switches. A hub functions as an amplifier which re-establishes the ideal signal shape of a bit if it has been corrupted by interference or dispersion on the transmission medium. A switch checks entire packets for correctness with regard to the checksum and directs packets without collision to another output if the destination address can be reached by this route. To this end, it must have the option of storing messages temporarily. As well as the costs involved in the hardware, a disadvantage when such elements are used is that the data stream is delayed. For this purpose, however, nodes with different data rates can be connected.

Today, networks are usually designed in such a way that each node is connected to the output of a switch, i.e. there is no direct connection between nodes. Switches themselves are in turn connected via a higher-level switch in such a way that a tree-shaped structure is created.

Ethernet protocol

Bus access

To transmit, a node checks whether there are signals on the bus. It starts to transmit when it deems the line to be clear. Because of the signal propagation time between two nodes, the situation may arise where two nodes deem the bus to be clear and start to transmit virtually simultaneously. The data frames transmitted in the process are destroyed. The nodes identify this, abort their transmission, and wait a certain amount of time – different for each node – until they begin with a new transmission attempt. This destruction of data frames reduces the effective transfer rate to a tolerable extent provided bus utilization is not too high.

This arbitration process limits the length of messages and the propagation time, i.e. the reach. There are no priorities among the messages. A maximum duration for transmission can, therefore, not be guaranteed.

Each node adopts from all the messages those which contain its own as the destination address for further processing.

Data frame

Figure 11 shows the slightly simplified structure of a data frame. The preamble is a periodic bit sequence (101010–1011) and thereby generates a signal to synchronize the receiver. Messages contain the address of their source and their destination. Each network card has a unique address. The receiving nodes compare the destination address with their own card address and accept the data frame if they match. With multicast and broadcast addresses, several receivers can also be addressed.

Figure 11: Frame format of Ethernet protocol

Preamble	Destination address	Source address	Length, type	Data, filler bytes	CRC
8 bytes	6 bytes	6 bytes	2 bytes	46–1,500 bytes	4 bytes

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PSI5

Overview

The Peripheral Sensor Interface 5 (PSI5) is a digital interface published by the PSI Consortium ([6]) for sensor applications in motor vehicles and can be assigned by the application to Class A (see Table 1). The PSI5 is based on already existing interfaces for peripheral airbag sensors, but has been developed as an open standard which can be used and implemented at no extra charge. The technical characteristics mentioned in the following, the low implementation expenditure and the low additional costs compared with an analog sensor connection make the PSI5 an attractive option for sensor applications in motor vehicles too.

Transfer system

The PSI5 is a two-wire current interface in which the same lines are used to power the sensors and for Manchester-encoded data transfer. The bus master in the ECU modulates a voltage to the sensor for this purpose. Data transfers from the sensor to the ECU are effected by current modulation of the supply lines. In this way, high EMC robustness and low electromagnetic radiation are achieved. A wide range of supply currents for the sensors can be supported.

The different PSI5 operating modes define the topology and parameters of communication between ECU and sensors (Figure 12):

- Communication modes: The asynchronous mode can be used for a unidirectional point-to-point connection. In the three synchronous bus modes (parallel, universal or daisy-chain cabling) several sensors can communicate on a time-controlled basis with the bus master bidirectionally and using TDMA processes.
- Data-word width: The PSI5 supports a variable data-word width of 8, 10, 16, 20 or 24 bits.
- Error detection: This can be effected either with a parity bit with even parity or with three CRC checksum bits.
- Cycle times: These are specified in μs .
- Number of time slots per cycle.
- Data-transfer rate: As standard 125 kbit/s or optionally 189 kbit/s.

For example, the operating mode “PSI5-P10P-500/3L” denotes a parallel synchronous mode with ten bits per data word and parity bit for error detection. The data are transmitted every 500 μs with three time slots per cycle and a low bit rate.

Figure 12: Designation of PSI5 operating modes

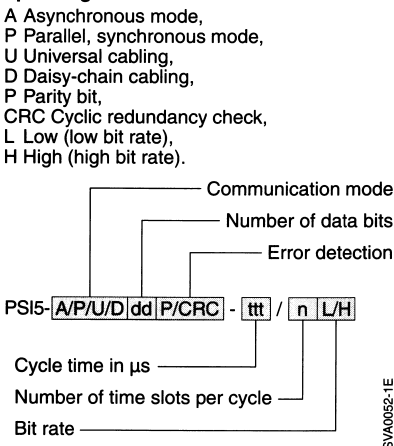
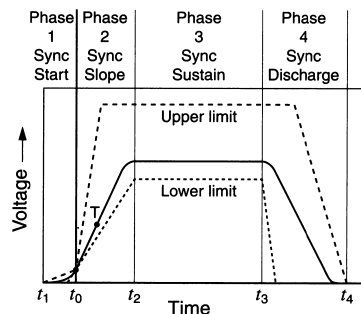


Figure 13: Synchronization signal of PSI5

T Trigger point.



During communication from sensor to ECU, a "low level" is represented by a normal (non-oscillating) current input of the sensor. A "high level" is generated by an increased current sink of the sensor (typically 26 mA). This current modulation is detected by the receiver in the ECU.

Each PSI5 data packet consists of N bits, in which there are in each case two start bits and one parity bit (or three CRC bits) and $N-3$ (or $N-5$) data bits. The data bits are transmitted with the least significant bit (LSB) first. Error detection with a parity bit is recommended for eight or ten bits, three CRC bits for longer data words.

In a PSI5 message, the data and value ranges have different meanings. One range serves to transmit the sensor output signals ($\approx 94\%$), one range the status and error messages ($\approx 3\%$), and one range the initialization data ($\approx 3\%$).

After each starting or undervoltage reset, the sensor conducts an internal initialization, after which the sensor is in an executable mode.

Whereas communication by the sensor with the ECU is effected with current signals, voltage modulation of the supply lines is used during communication by the ECU with the sensors. A logic 1 is represented by the synchronization signal, a logic 0 by the absence of the expected synchronization signal within the designated time slot. The synchronization signal consists of four voltage phases (Figure 13):

- Sync Start (nom. $3\ \mu\text{s}$, $< 0.5\ \text{V}$),
- Sync Slope (nom. $7\ \mu\text{s}$, $> 0.5\ \text{V}$),
- Sync Sustain (nom. $9\ \mu\text{s}$, $> 3.5\ \text{V}$), and
- Sync Discharge (nom. $19\ \mu\text{s}$, $< 3.5\ \text{V}$).

MOST

Overview

Application

The MOST bus (Media Oriented Systems Transport) was specially developed for the networking of multimedia applications in motor vehicles (infotainment bus). Alongside the classical entertainment functions such as radio receivers and CD players, infotainment systems also provide video functions (DVD and TV), navigation functions, and access to mobile communication and information. The MOST bus supports the logical networking of up to 64 devices and provides a fixed and reserved transmission bandwidth. MOST defines the protocol, the hardware, the software, and the system layers. MOST is jointly developed and standardized by automobile manufacturers and suppliers within the MOST Cooperation [7]. With a data rate of more than 10 Mbit/s, the MOST bus is a Class D bus system (see Table 1).

For data transfer, the MOST bus supports the following transmission channels:

- Control channel to transport control commands,
- Multimedia channel (synchronous channel) for the transmission of audio and video data,
- Package data channel (asynchronous channel), for example to transmit configuration data for a navigation system and to update software in control units.

Requirements

The transmission of multimedia data – both audio and video data – requires a high data rate and also synchronization of the data transfer between source and sink as well as between a number of sinks.

Transfer system

Physical layer

The MOST standard specifies both optical and electrical technologies of the physical layer (transmission layer). The optical transmission layer is widespread and currently uses fiber-optic cables (polymer optical fibers, POF) made of polymethyl methacrylate as its transfer medium. These have a 1 mm core diameter and are used in combination with LEDs and silicon photo diodes as receivers (see Optical fibers/waveguides).

The outstanding feature of MOST50 is its suitability for the electrical transmission of data. This enables data transfer across unshielded, twisted copper cables (UTP, unshielded twisted pairs). Whereas MOST25 technology has continued to develop in Europe for a many years and has become established in the Korean market, the Japanese market in particular prefers MOST50, the second generation of the multimedia standard.

The identification number, for example in the case of MOST25, stands for a transfer rate of approx. 25 Mbit/s. The exact data rate depends on the sampling rate that the system uses. With a sampling rate of 44.1 kHz, the MOST frame (data frame) is transferred 44,100 times per second; a frame length of 512 bits results in a data rate of 22.58 Mbit/s. For MOST50, the same sampling rate results in double the data rate, as the frame is 1,024 bits long. Higher data rates of 150 MBit/s (MOST150) are currently also available.

Special features of MOST150

In addition to the higher bandwidth of 150 Mbit/s, MOST150 contains an isochronous transport mechanism to transfer compressed data of HD videos efficiently. MPEG transport streams (MPEG, Moving Picture Experts Group) are transported directly here. With a corresponding MPEG4-based video codec, it is possible to transfer resolutions of up to 1,080 p (1,080 screen lines), as delivered by BluRay players for example. Alongside this, MOST150 provides an Ethernet channel for the efficient transmission of IP package data (IP = internet protocol).

In contrast to the MAMAC protocol (MOST Asynchronous Medium Access Control) used in the case of MOST25, the Ethernet channel is able to transfer Ethernet frames. The Ethernet channel transfers unmodified Ethernet data blocks, which means that software stacks and applications from the fields of consumer electronics and IT can be integrated seamlessly in vehicles with much shorter innovation cycles. TCP/IP stacks or protocols that use TCP/IP (TCP = Transmission Control Protocol) can thus communicate via MOST150 without changes.

The MOST Network Interface Controller (NIC) is a hardware controller that is responsible for control of the physical layer and implements important transfer mechanisms.

Protocol
Data transfer

Data transfer on the MOST bus is organized in data frames that are created by the timing master with a fixed data rate and passed on by the devices in the ring.

Data frames

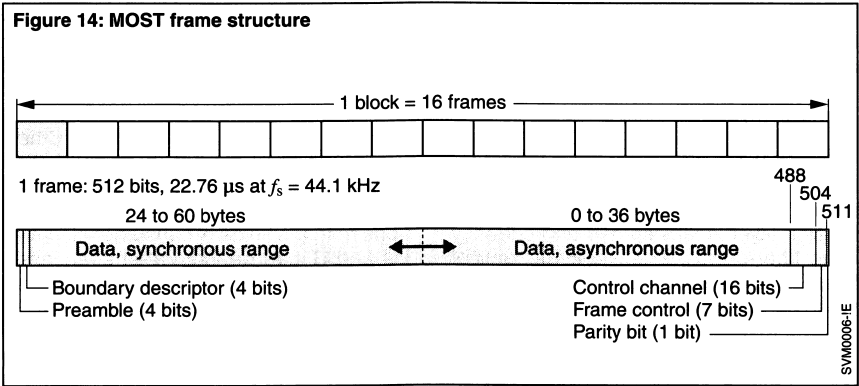
The timing master usually creates data frames with a clock rate of 44.1 kHz, more rarely also 48 kHz. The size of the data frames thus determines the bus speed of a MOST system. In the case of MOST25, the size of a data frame is 512 bits (Figure 14). The synchronous and asynchronous areas of MOST 25 jointly use 60 bytes of the data frame. The division between the synchronous channels and the asynchronous channel is determined by the value of the boundary descriptors with a resolution of 4 bytes. The synchronous area must have at least 24 bytes (six stereo channels). This means that between 24 and 60 bytes are permitted for the synchronous area and between zero and 36 bytes are permitted for the asynchronous area. The preamble is used for synchronization; the parity bit is used to recognize bit errors.

Transmission of control messages
The control channel is used to signal device statuses and for the messages re-

quired for system administration. So that the control channel does not occupy too much bandwidth per frame, it has been distributed to 16 frames grouped to form a block. Each frame transports two bytes of the channel (Figure 14). In order to ensure recognition of the block start, the preamble of the first frame of a block bears a special bit pattern. In the case of MOST25, the control channel has a gross bandwidth of 705.6 kbit/s.

Transmission of multimedia data
The synchronous channels are used for realtime communication of audio and video data, whereby the data interchange is controlled via the corresponding control commands on the control channel. A synchronous channel can be assigned a certain bandwidth, which occurs with a resolution of one byte of a data frame. A stereo audio channel with a resolution of 16 bits, for example, requires four bytes. In the case of MOST 25, depending on the value of the boundary descriptor, a maximum of 60 bytes are available for synchronous channels; this corresponds to 15 stereo audio channels.

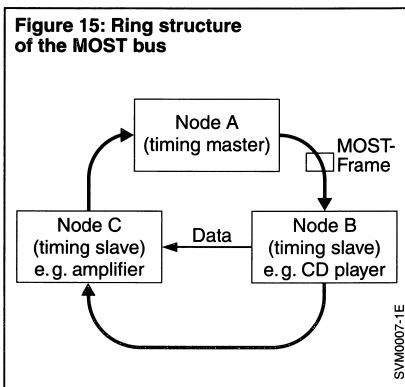
Transmission of package data
Data are transferred packet-wise on the asynchronous channel. It is therefore suitable for the transmission of information that has no fixed data rate but requires high data rates at short notice. Examples are the transmission of track information of an MP3 player or a software update.



In the case of MOST 25, the asynchronous channel has a gross bandwidth of up to 12.7 MBit/s and it currently supports two modes: a slower 48-byte mode in which 48 bytes are available in each package for the net data transmission as well as a 1,014-byte mode that is more complex to implement. In order to ensure reliable transmission and flow control for the typically large asynchronous channel data volumes, an additional transport protocol (Data Link Protocol) is usually deployed; this is implemented in a driver layer at a higher level. This is either the MOST High Protocol (MHP), which has been specially developed for the MOST, or the common TCP/IP protocol that is placed on a corresponding adaptation layer called the MOST Asynchronous Medium Access Control (MAMAC).

Topology

MOST is organized in a ring structure (Figure 15). This is a point-to-multipoint data flow system (i.e. the streaming data have one source and a number of sinks) and all the devices therefore share a joint system frequency that they acquire from the data flow. The devices are thus in phase and can transfer all data synchronously. This makes mechanisms for signal buffering and signal processing superfluous. A certain device acts as "timing master" and generates the data frames used for data transfer and to which the other devices synchronize.



Addressing

The devices are addressed on the MOST bus via a 16-bit address. Various types of addressing are available: Logical and physical addressing as well as group addressing for simultaneous addressing of a defined group of control units.

Administration functions

The MOST standard defines the management mechanisms (network and connection masters) necessary for the operation of a MOST system. These mechanisms are described below.

Network master

The network master is implemented by a marked device in a MOST system and is responsible for the configuration of the system. In current systems, the network master is usually implemented using the head unit (i.e. control panel) of the infotainment system. This device is often also the timing master at the same time. The other devices of the MOST system are referred to as network slaves in this context.

Connection master

The connection master manages the synchronous connections that exist in a MOST system at any particular point in time.

MOST application layer

For the transfer of control commands, status information, and events, the MOST standard defines a corresponding protocol on the application level. This protocol enables triggering of a certain function of an application interface (i.e. of an FBlock = function block) that is provided by any device within the MOST system.

The protocol for MOST control messages includes the following elements of a control message:

- The address of a device in the MOST system (DeviceID)
- An identifier for an FBlock (FBlockID) implemented by this device and its instance in the MOST system (InstID)
- The identifier for the function called up within the FBlock (FunctionID)
- The type of an operation (OpType).

Function block

A function block (FBlock) defines the interface of a certain application or of a system service. The sinks and sources for multimedia data are each assigned to an FBlock that provides the corresponding functions for their administration. An FBlock can therefore have a number of sources and sinks enumerated via a source and sink number.

An FBlock has functions that deliver information regarding the number and type of sources and sinks that it provides (SyncDataInfo, SourceInfo and SinkInfo). Over and above this, each FBlock with a source has an "Allocate" function that it uses to request a synchronous channel and connect the source to that channel. Accordingly, an FBlock with a sink has a "Connect" function to connect the sink to a certain synchronous channel and a "Disconnect" function to break off this connection.

An FBlock is addressed by means of an 8-bit FBlockID, which specifies the type of the FBlock, and an additional 8-bit InstID.

Function classes

To standardize the way in which functions are defined, the MOST standard specifies a series of function classes for properties. These determine which properties the function has and which operations are permissible.

Applications

As well as defining the lower layers necessary for data transfer, the MOST standard defines the interfaces for typical applications from the area of vehicle infotainment systems, e.g. a CD changer, amplifier or radio tuner.

The FBlocks defined by the MOST Cooperation are summarized in a function catalog.

Standardization

The MOST standard is maintained by the MOST Cooperation, which also publishes the corresponding specifications. The specifications are available on the homepage of the MOST Cooperation [7].

The MOST Corporation was founded in 1998 by BMW, Daimler, Becker Radio, and OASIS Silicon Systems with the aim of standardizing MOST technology.

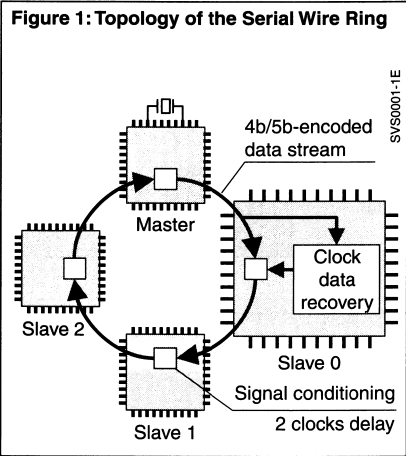
Serial Wire Ring

Internal buses do not leave the ECU. They connect the integrated circuits (ICs) on the board to each other. These buses transmit data from input circuits (e.g. analog-digital converters) to the controller or data to activate output stages from the controller to the output stages. Since these buses are only used inside one ECU, voltage levels, signal type (symmetrical or asymmetrical), impedances, and bit rate can be configured differently, depending on the requirement.

Features

The Serial Wire Ring (SWR) is the modern successor to the Serial Peripheral Interface (SPI). Its advantages are the higher bit rate and only two pins per user as opposed to four pins (CLK, MOSI, MISO, CS) in the SPI. As the price for these advantages the SWR requires a more complex logic in the transmitter and in the receiver, particularly to recover the clock signal from the data stream.

Only two pins per user provide for small housings and less wiring on the board. This is made possible by a ring topology as pictured in Figure 1. This has the additional benefit of the master being able to read back all data and thereby discover transmission errors. This is an important feature for safety-related systems.



Topology

The ring consists exclusively of point-to-point connections, providing for high data rates. Each connection transmits the data from precisely one source to precisely one destination in only one direction (Figure 1):

Master → Slave 0 → Slave 1 → ... → Slave *N* - 1 → Master.

The ring contains one master and 1 to 16 slaves. Since all are similarly connected to each other in the ring, it is optionally possible for alternately a different module in the ring to assume the role of master.

Each user in the ring forwards the received signal with two clocks delay to the next user. The level of the signal is thereby conditioned. Even small time fluctuations of the signal edges (jitter) are reduced with the aid of clock data recovery (CDR). In this way, different signal levels can be realized within a ring.

4b/5b encoding of data

Clock and data are jointly transmitted via a line in the ring. The receiver extracts the data and the clock from this signal by means of clock data recovery (CDR). To enable the clock to be recovered even in the event of many consecutive "0" or "1", a special 4b/5b encoding as depicted in Table 1 is used: Every fourth bit is inverted and then sent again. With this encoding there is a change from "0" to "1" or vice versa after five clocks at the latest. The drawback is that five bits have to be sent over the bus to transmit four data bits.

Table 1: 4b/5b code

The lowest-value bit is transmitted first.

0000 → 00001	0001 → 00010
1000 → 10001	1001 → 10010
0100 → 01001	0101 → 01010
1100 → 11001	1101 → 11010
0010 → 00101	0011 → 00110
1010 → 10101	1011 → 10110
0110 → 01101	0111 → 01110
1110 → 11101	1111 → 11110

Transmission is performed according to the following scheme: The lowest-value bit is always transmitted first and the highest-value bit is transmitted last.

Clock rate

The clock rate is not tied down to specific values, but can be chosen to suit the required data rate and latency. The lower limit is 1 MHz, the upper limit is determined by the slowest user and the line routing.

Signal transmission from precisely one source to precisely one destination facilitates higher data rates than with a branched line such that the Serial Wire Ring can be operated at 10 to 100 times the clock frequency of the Serial Peripheral Interface. The demand for higher speed mentioned at the start is thus fulfilled.

Data transmission

The interframe symbol and the data frame or the interrupt frame are transmitted alternately by the master on the data line (2).

Addressing

The slaves are addressed via an address field in the data frame. Each slave receives its address automatically via its position in the ring during the initialization of the ring. The first slave receives the address 0, the last of *N* slaves receives the address *N* – 1.

Data frame

The data frame serves to transmit user data between master and slave. With the same data frame the master can also send data to several slaves and receive data from several slaves. At the same time it is possible to transmit data from slave to slave, but only in the circulation direction of the ring.

The master continuously sends frames through the ring. If no data have to be transmitted, it sends “zero frames”.

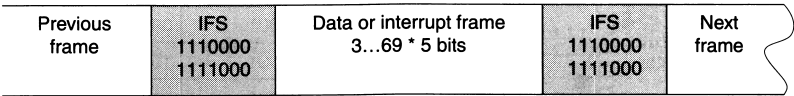
Interrupt frame

Interrupt frames are regularly sent by the master within a fixed time interval. Each slave which has reserved one or more bits in the interrupt frame can use such a bit to trigger a specific reaction in the master. This reaction usually consists of delivering or collecting data.

Interframe symbol

To enable each user in the ring to detect the start of a frame, the interframe symbol (IFS, Figure 2) is situated between two frames. It is 14 bits long and differs from each possible 14-bit sequence of the 4b/5b-encoded signals in at least two bits. This ensures that a 1-bit error does not lead to the appearance of an interframe symbol in the regular 4b/5b data stream. Each user in the ring compares the last 14 received bits with the interframe symbol. If they match, the user begins to evaluate the frames that now follow. In the event of errors, it aborts the evaluation and waits for the next interframe symbol.

Figure 2: Structure of a data transmission
IFS Interframe symbol.



Data frame

Identifier

Figure 3 shows a data frame in detail. The leading 1 identifies the frame as a data frame. A 01 would indicate a zero frame and a 0010 an interrupt frame.

Data frame counter

The data frame counter (DFC) is a 2-bit counter which the master increments before it sends a new data frame. This is important in the event of a transmission error that the master notices when reading back. It then repeats the data frame with the same DFC. If the error has occurred on the way from the master to the slave, the slave now receives the data frame for the first time and evaluates it. If the error has occurred on the way from the slave to the master, the slave now receives the data frame for the second time, detects this by the unchanged DFC, and now does not evaluate it for a second time.

Slave address

The slave address SLADR addresses the slave. The primary addresses 0 to $N-1$ address precisely one slave at the corresponding position in the ring. Higher values up to 31 are used for group addresses. While the ring is being initialized, the master can instruct one or more slaves to execute a particular operation automatically if a certain group address appears, for example to output bits 12 to 16 to five output stages. In this way, the master can carry out complex data trans-

fers later without further instructions and thus very quickly simply by using the associated group address. The participating slaves then "know" what is to be done.

Parity bit

PAR is a parity bit for the first eight bits. It is sufficient in order to detect 100 % of all single-bit errors. Double-bit errors are detected by the master when reading back and lead to a bus reset. Therefore they do not have to be detected by PAR. This procedure is possible because double- and multiple-bit errors are very rare.

Data field

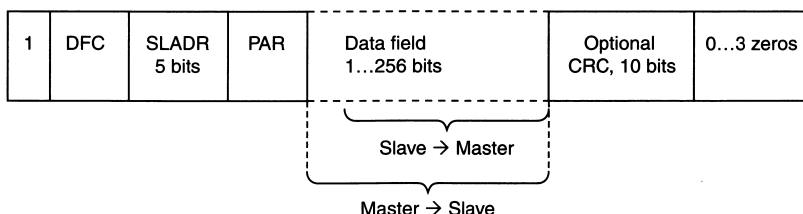
The actual data field comes after PAR. It can contain any number of bits from 1 to 256.

Primary address

In the event of a primary address, i.e. if the master only addresses this slave, the slave processes the entire data field and if necessary places an answer at the end of the data field. In the process it overwrites part of the data field so that the master can no longer read back its message to the slave. If this is not permitted for security reasons or if the slave's answer is already longer than the master's message, the master must configure the data field bigger and for example append zeros. The slave then overwrites only this areas and no old data are lost. However, this gives rise to a larger data field, i.e. a longer transmission time.

Figure 3: Data frame

DFC Data frame counter,
SLADR Slave address,
PAR Parity bit,
CRC Cyclic redundancy check.



Group address

In the event of a group address, each slave can, according to its previously learned instructions, evaluate and change any bits of the data field.

Cyclic redundancy check

The concluding 10-bit CRC (cyclic redundancy check) is supported by slaves for which this is useful. There are also simple slaves which do not support the CRC in order to save costs. The CRC is required to back up critical data on their way from the slave to the master. Because, while the master can detect all the other transmission errors when reading back, this is not possible with the answer data from a slave. The slaves which belong to a group address must all jointly use the CRC, or not.

Filler bits

Because of the 4b/5b encoding the data frame must always contain a multiple of four bits. It may therefore be necessary finally to append up to three more zeros in order to reach the next multiple higher of four.

Sequence control in the master

As transmission rates increase, it is becoming increasingly more difficult for a CPU to make available the transmission data in good time via a simple send and receive register and to collect the received data fast enough. Therefore the SWR master automatically accesses the memory. This memory also contains one or more chained lists with instructions as to which transactions the master is to execute (queues).

Once activated, the master works through a queue instruction by instruction down to the last instruction or to an instruction with a set stop bit. A software command, an external trigger (e.g. by a timer) or the already described prompt by a slave by means of interrupt frame can reactivate the queue.

The end of a queue can refer back to the start and thereby form a closed loop. In this way, the same instructions can be executed again and again. If an instruction is disrupted by a transmission error, the master repeats it automatically.

Each instruction contains a priority. This does not play a role as long as only one queue is active. However, as soon as several queues are active and therefore several instructions are due to be executed at the same time, the master selects the instruction with the highest priority.

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Architecture of electronic systems

General

Owing to the increasing demand for safety, comfort, entertainment, and environmental protection, electronic systems in motor vehicles realize an increasing number of functions and are characterized by a high level of networking and complexity. Optimized processes, methods, and tools of system architecture are required to keep on top of this structure in the future too.

History

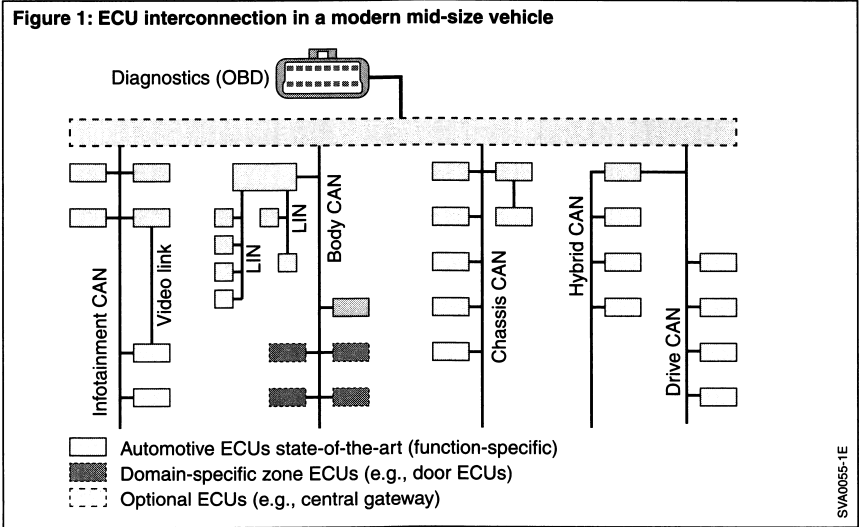
Over the many decades of automobile history, there has been a manageable number of electrical systems in motor vehicles: ignition, lighting, windshield wipers, horn, fuel gage, various indicator lamps, and a vehicle radio. Semiconductors were used initially – except in vehicle radios – only for rectification (direct-current generator replaced by alternator from approximately 1963) and then later for electronic control (transistorized ignition from 1965).

Certain in-vehicle functions were realizable with electromechanical means or with discrete electronic components either not at all or only with disproportion-

ately high complexity. Thus, for example, the first electronic antilock braking system (ABS) had already been developed in 1970, but was never ready for series production on account of its size, weight and cost. By the mid-1970s the development of integrated circuits for a broad range of applications had also reached and revolutionized automotive engineering.

One of the first instances of the networking of electronic systems came about during the development of the traction control system (TCS). This networking was initially realized by purely mechanical means. The throttle valve in the air-intake system of the internal-combustion engine was fitted with a device which could be activated directly by the traction control system. It was not discernible to the engine management whether the driver or the traction control system was moving the throttle valve.

The next stage involved the realization of an electronic connection to the engine control unit via a PWM interface (pulse-width modulation) to improve dynamic response. This could be used to transfer



the signal to the engine control unit for reducing the drive torque. This was then implemented in the form of an air-supply throttling, an injection blank-out or an ignition-angle adjustment.

On account of the ever more stringent exhaust-emission regulations the possibilities represented up until that point of coupling between the traction control system and the engine management were no longer sufficient. What was now required was to transmit to the engine management how a reduction of the drive torque requested by the traction control system is effected in the air, fuel or ignition path. It was therefore necessary to come up with a more powerful interface via which a desired torque and a dynamic-response request could be transmitted from the traction control system to the engine management. By contrast, the actual torque, the engine speed and the current setting reserve were to be transmitted to the TCS control unit. It proved complex and expensive in terms of the number of cables required to transfer these different data via discrete and, for example, pulse-width-modulated interfaces. The CAN bus system (Controller Area Network) was introduced in 1991 as an alternative to discrete cabling. In this way, the foundations for the modern networking of systems in motor vehicles were laid.

Technology of the present day

In today's vehicles, virtually all the ECUs are networked directly or indirectly (e.g. via gateways) with each other (Figure 1). Gateways facilitate the exchange of data between different communication systems and beyond vehicle limits (connection to radio systems and the Internet). Networking goes to some extent so far that 60 or more ECUs communicate via several CAN or CAN FD bus systems (CAN with Flexible Data-Rate) and further communication systems, such as Flex-Ray, MOST (Media Oriented Systems Transport) or LIN (Local Interconnect Network), with each other. Aside from the classic communication systems, Ethernet is also used for various vehicle functions which require a large bandwidth. This is the case for example with a 360° camera

for automatic park assist, which enables the driver among other things to have a bird's-eye view of the vehicle for example in the infotainment-system display.

Because of the powerful networking between the ECUs, some new performance features can even be achieved completely without additional hardware, i.e. purely by means of data communication and software. An example of this is the tire-pressure monitoring system (TPMS). Since the end of 2014 a tire-pressure monitoring system has been mandatory in all vehicles. There are two ways of realizing such a system: firstly as an indirect solution and secondly as a direct solution. The indirect solution uses the wheel-speed sensors of driving-dynamics control (Electronic Stability Control, ESC) and thus does not require any further hardware. As soon as a wheel loses air, the wheel diameter decreases, as a result of which the wheel must turn more quickly and consequently the air loss can be determined by means of an algorithm.

Also classed as state-of-the-art are numerous Advanced Driver Assistance Systems (ADAS). For example, the car manufacturers offer functions such as Adaptive Cruise Control (ACC), Lane Keeping Support, or the combination of adaptive cruise control and lane keeping support known as Integrated Cruise Assist (ICA), and many others. All this can be realized with a matching E/E architecture with suitable sensors, such as for example a stereo video camera, radar sensors, and ultrasonic sensors.

Development trends

The increasing number of electronic and electrical components in modern vehicles and the constantly increasing complexity necessitate a continuous further development and constant technological advances in E/E architectures. For this reason, E/E architectures of vehicles have in the past obviously changed with regard to the communication technologies and also in their systemic manifestation. Further developments will also be constantly identifiable in the future. The following text will examine the evolution of E/E architectures and provide an outlook of future developments and trends (Figure 2).

Distributed E/E architectures – modularity and integration

The picture of the first E/E architectures and their comparably lower level of complexity was initially characterized by their strong modularity (Figure 2, bottom third). Logic functions were distributed to many individual ECUs – function-specific ECUs – in the vehicle such that virtually every function had its own ECU with performed the function. In the ensuing period, with the sharp increase in functions, new functions were frequently integrated in ECUs that already existed in the vehicle. The reasons for this in particular are the rapidly growing number of ECUs and the associated rising costs. An example of functional integration is the integration of a parking-assist function in the “Body Control Module”, which is essentially responsible for controlling and monitoring the functions and components of the

body electronics (e.g. light-actuator technology, door-actuator technology).

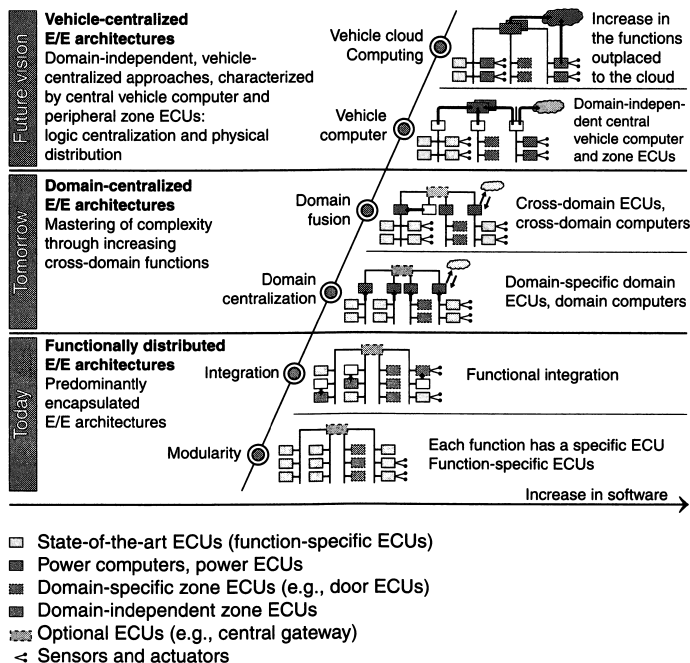
For the reasons mentioned this stage of development of the E/E architectures is called Functionally distributed E/E architectures (Figure 2).

Domain-centralized E/E architectures

In the ensuing step – the domain-centralized and cross-domain-centralized E/E architectures – not only do the number of electronic and electrical components and the number of functions continue to rise sharply, but also increasingly the dependencies of the functions within the individual domains (Figure 2, middle third). The term “domain” refers to the grouping of similar functions. Typical domains are shown in Figure 3.

Furthermore, the interfaces and dependencies between the domains increase sharply. This development is already

Figure 2: Bosch E/E architecture roadmap



clearly discernible in today's vehicle architectures and will take on an ever more significant role in future. An example of this is the cross-domain function "Vehicle Motion Control", which will be described in more detail later. Thus, in this case, sensors, actuators, and functions from the "Powertrain" and "Chassis and Safety" domains interact directly with each other.

In other words, increasingly vehicle-wide functions extending over a number of domains stand out. The associated strong logic interaction and networking as well as the resulting dependencies give rise from a functional perspective to a centralization. This means that, instead of the originally modularly distributed arrangements, increasingly functions are being bundled into domain ECUs, domain computers, or even into cross-domain ECUs or cross-domain computers.

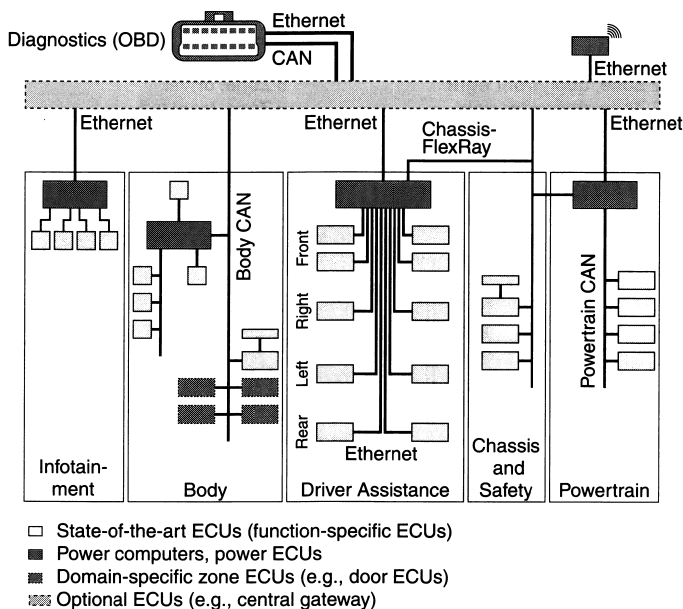
Therefore the term used for the E/E architectures of tomorrow is Functionally domain-centralized E/E architectures (Figure 3).

Vehicle-centralized E/E architectures

If one takes a further look into the future, the vehicle is in particular characterized by a high degree of automation, networked systems – vehicle-internal and vehicle-external – and by multimedia and infotainment applications. These vehicle properties impose the highest demands on the E/E architecture and on the communication network. In this way, requirements with regard to maximum permissible latencies or the number of hops (path from one network node to the next) acquire ever greater importance. This constitutes a huge challenge for classic E/E architectures. For this reason, the trend is towards functional centralization (Figure 2, top third).

If all the logic were to be brought together on a powerful central vehicle computer, an ideal state would be achieved for example with regard to the mentioned latency requirements and the number of hops. All the functional interfaces would then be located within this central vehicle

Figure 3: Schematic diagram of a functionally domain-centralized E/E architecture



computer. This is the basic idea behind centralized E/E architectures, consisting of a central vehicle computer which with extremely high computing capacity constitutes a vehicle-wide functional control system and a number of zone ECUs. While a large part of the complex logic of the highly automated and comfortable vehicle of the future will therefore be realized in the central vehicle computer, the peripheral zone ECUs function from a communication standpoint as gateways and from an energy standpoint as supplying and driving elements for the vehicle sensor and actuator technologies. In order to guarantee the high communication demand and hence the high bandwidths, technologies such as Ethernet will in future take up greater shares of the communication network and entail new concepts (Figure 4).

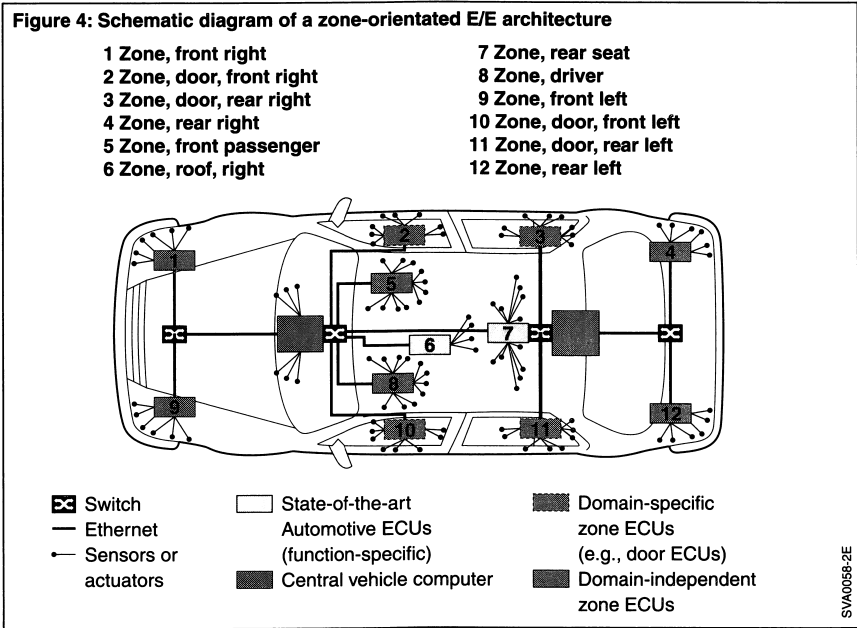
Furthermore, even outplacements of logic elements to the back end – the so-called cloud – are conceivable in order to be able to calculate cross-vehicle information and algorithms, for example the calculation of traffic forecasts, not locally but

centrally and to make available a number of vehicles or vehicle fleets.

The following section describes using highly automated driving functions how these bring an influence to bear on the E/E architectures in modern vehicles.

Effect of highly automated driving functions on the E/E architecture

Nowadays car manufacturers increasingly advertise with driver-assistance functions which make it easier for drivers to negotiate road traffic safely and comfortably. As good as all the functions that can be bought today by the end customer are assistance functions in which the driver is supported but not replaced. This is to change in the near future. Car manufacturers and suppliers are meticulously developing highly automated driving functions to further relieve the load on drivers. A distinction is made here between assisted (driver has to monitor) and piloted (driver does not have to monitor) driving. The German car industry has in a panel of experts come up with a uniform understanding of the stages of automation [1].



Starting at Stage 0, in which the driver exclusively assumes longitudinal and lateral control of the vehicle, right up to Stage 5, in which the system can automatically manage all situations during driving and a driver is no longer required (Table 1). The factors driving the development of highly automated driving are, aside from greater road safety, above all increasing comfort and convenience and more time which the driver can use for other activities. Activities like for example writing e-mails, surfing the Internet, and many more are then possible while driving.

For highly automated driving to be possible at all, it needs a powerful and reliable E/E architecture. The following section will address which E/E architecture blocks and which adaptations are required for this.

E/E architecture blocks

To realize a powerful and reliable E/E architecture, certain E/E architecture blocks are needed. These include among others communication, the vehicle electrical system, the sensor and actuator set, and per-

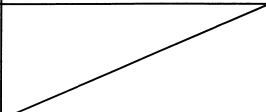
formant ECUs. For highly automated driving functions it is important that parts of these E/E architecture blocks are always available. This gives rise to high safety requirements, which can only be satisfied by fallback levels (redundancies) in the event of a fault. Such concepts are also called fault-tolerant. Here, redundancy can refer to communication, the vehicle electrical system, and the software and the hardware.

The E/E architecture blocks and corresponding fallback levels are described in the following.

Fault-tolerant communication network

Highly automated driving functions in vehicles must ensure that required information is always available between two components. For example, it must always be possible for the brake and the steering to receive the necessary information as to whether the vehicle has to be braked or steered. Redundant communication can be used to satisfy this safety requirement. A distinction is made here between a vari-

Table 1: Degree of automation acc. to VDA (source: VDA)

Stage	Degree of automation	Description	
		Driver	Automation
0	Only driver	Driver constantly performs longitudinal and lateral control	No intervening vehicle system active
1	Assisted	Driver constantly performs longitudinal or lateral control	System assumes the other function in each case
2	Partially automated	Driver must constantly monitor the system	System assumes longitudinal and lateral control in a specific application
3	Highly automated	Driver must constantly monitor the system Driver must potentially be in a position to take over	System assumes longitudinal and lateral control in a specific application System identifies system limits and prompts the driver to take over with a sufficient time reserve
4	Fully automated	No driver required in the specific application	System can automatically manage all situations in the specific application
5	Driverless		
		System can automatically manage all situations throughout the entire journey	
		No driver required	

ety of topologies: ring, star, bus, and fully meshed topology (Figure 5, see also Networking in motor vehicles).

Fault-tolerant vehicle electrical system

Like the communication network, the vehicle electrical system must also have a fault-tolerant design. The vehicle electrical system can be divided into three elements (Figure 6): storage elements (e.g. battery), coupling elements (e.g. DC/DC converter), and source elements (e.g. alternator).

To enable the vehicle to still be controlled accordingly in the event of a fault, the safety-related components, which for example implement the braking and steering functions, are supplied by two completely independent storage devices. These two storage devices are in the event of a fault separated via a coupling element, meaning that the fault is encapsulated and consequently the fault

is prevented from spreading to the other supply channel. On account of the redundant actuator technology, in this case the safety-related functions like braking and steering continue to be available – for a limited time at least – for a transition to a safe state, even if a supply channel fails.

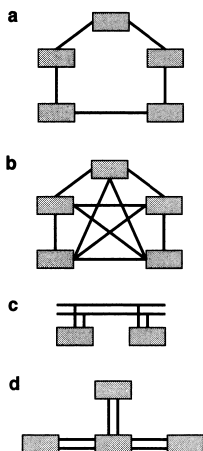
Sensor redundancy concept

An important influencing factor for highly automated driving is the vehicle environment. This is detected by a variety of sensors such as radar, lidar, camera, and ultrasonic sensors. GPS and inertial sensors are also used to pinpoint the vehicle position. In combination it is possible to determine both what is situated around the vehicle and where the vehicle itself is situated.

A redundant sensor set can also be realized with the basis of the redundant communication network and the redundant vehicle electrical system. It is important

Figure 5: Fault-tolerant communication: ring, star, bus, and fully meshed topologies

- Ring topology,
- Fully meshed topology,
- Bus topology,
- Star topology.

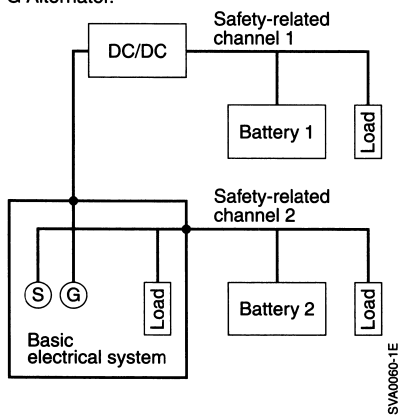


□ Component
— Communication line

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Figure 6: Fault-tolerant vehicle electrical system

S Starter,
G Alternator.



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ant here that a field of view (FoV) is always covered by different sensor principles so that the environment can be reliably detected in all situations. For example, the sensors should be split between the two supply channels in such a way that the field of view is covered during normal operation by sensors A, B, C, and D, in fault scenario I (fault on supply channel 1) by sensors B and C, and in fault scenario II (fault on supply channel 2) by sensors A and D. Which sensor principles, sensor combinations, and sensor distributions are ideal to be able to detect the environment in all situations is currently the object of development.

Performant ECUs

The vehicle environment and the vehicle position are elementary information for highly automated driving. The sensor data obtained are fused in performant ECUs into an environment model. A lot

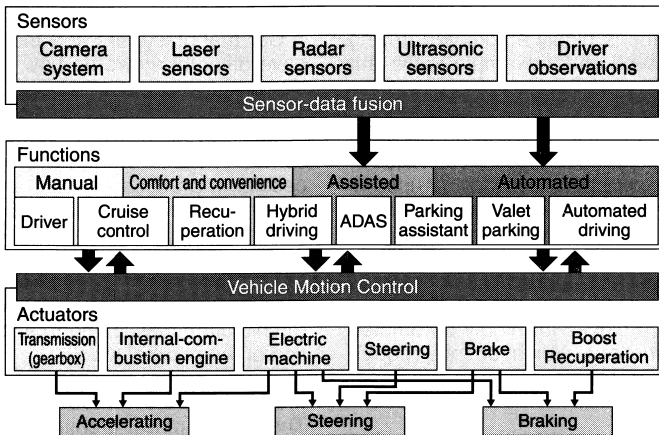
of computing capacity is required for this processing operation. Fault tolerance is important here so that the sensor-data fusion can also be computed in the event of a fault. Among others, for example, either a fault-tolerant ECU (e.g. two boards in one housing) or a combination of two ECUs with one main path and one substitute path can be used.

To be able to deliver this computing capacity at all, automotive electronics will in future increasingly turn to other disciplines, for example consumer electronics. This will also involve the use of microprocessors in addition to automotive-certified microcontrollers.

Vehicle Motion Control

Irrespective of whether assisted or highly automated driving is now employed when the driver wants to go from A to B, a "Vehicle Motion Control" (VMC) [2] (Figure 7) is always demanded. This VMC assumes

Figure 7: Vehicle Motion Control (source: [2])



lateral and longitudinal control of the vehicle without permanent monitoring by the driver by coordinating and monitoring access to actuators (brake, steering, and drive). The environment model from the sensor-data fusion serves as the input for deriving an adequate driving decision.

Actuator redundancy concept

Highly automated driving functions such as highway pilot require a redundant brake and steering in the network of actuators which are coordinated by VMC. Redundant braking capability is provided here for example by the combination of iBooster (vacuum-independent, electro-mechanical brake booster from Bosch, see iBooster) and driving-dynamics control (ESC) (source [2]). Furthermore, fault-tolerant steerability for example is provided by electric steering in which all the components are redundantly designed (among others power supply, communication, windings, logic, etc.).

E/E architectures for highly automated driving

For the various highly automated driving functions such as for example traffic-jam pilot or highway pilot the previously mentioned E/E architecture blocks are required to realize a powerful and reliable E/E architecture. The described stages of the degree of automation can be used to subdivide the driving functions and derive appropriate requirements with regard to the E/E architectures. Reference is made here once again to the importance of the redundant design of the individual E/E architecture blocks for highly automated driving functions which do not require monitoring by the driver.

Development of E/E architectures

Definition of "E/E architecture"

As the amount of electronics and networking in the vehicle increases, so too the demand for powerful development processes and their description methods for the architecture of electrical and electronic systems increases.

The term "architecture" generally refers to the art of building. In the construction industry, the architect designs a building by drawing up plans for the different views and contractual work based on the client's wishes and boundary conditions. A plan abstracts the reality with regard to a particular aspect (e.g. geometric conditions or electric cabling). The building can finally be erected on the basis of the plans of all the necessary aspects.

When carried over to a motor vehicle, this is referred to as the "E/E architecture". "E/E" denotes the electrical and electronic aspects of the motor vehicle. The "plans" of the E/E architect are referred to in the following with the general term of "model".

Car manufacturers and their suppliers have different views on how many models of which type are needed to describe completely the electrical and electronic systems in the vehicle. The models presented in the following have proven successful in practice and are a necessary framework for describing the E/E scope.

The term architecture is often used in the literature and in publications to denote the models themselves. Here, a clear distinction is made between work operation (architecture development) and presentation of the result (model).

Models of E/E architecture

The models of E/E architecture reflect the results of the different integration aspects of the electronic systems in the vehicle (Figure 8). These aspects are usually dealt with simultaneously because E/E architecture development in the concept phase of a vehicle addresses both the geometry (the "body structure") and new systems which are to be implemented in the vehicle. In the course of vehicle development, the situation may for instance arise where an electronic system in the

chosen technology cannot be integrated into the available space. Compromises must be found in this case.

Feature and requirement models

Feature model

The feature model defines which performance features (features, fixed term in E/E architecture) the vehicle is to have later. These performance features are vehicle properties which can be experienced by the driver and the passengers – thus for example ACC Stop and Go (see Adaptive Cruise Control). The vehicle scope is defined with the feature model. All further models can be derived and developed on the basis of the features.

Requirement model

All the necessary vehicle requirements are set out in the requirement model. These put the features in concrete terms and serve as an input variable for the functional model. Here, for example, the ACC feature can be put in concrete terms with regard to the driving speed. Because the

Stop-and-Go variant of ACC is involved, the lower limit of the speed range must be 0 km/h. The upper limit differs from car manufacturer to car manufacturer (e.g. 130 km/h). If the feature for example were not a Stop-and-Go ACC variant, the speed range could be 30 to 200 km/h.

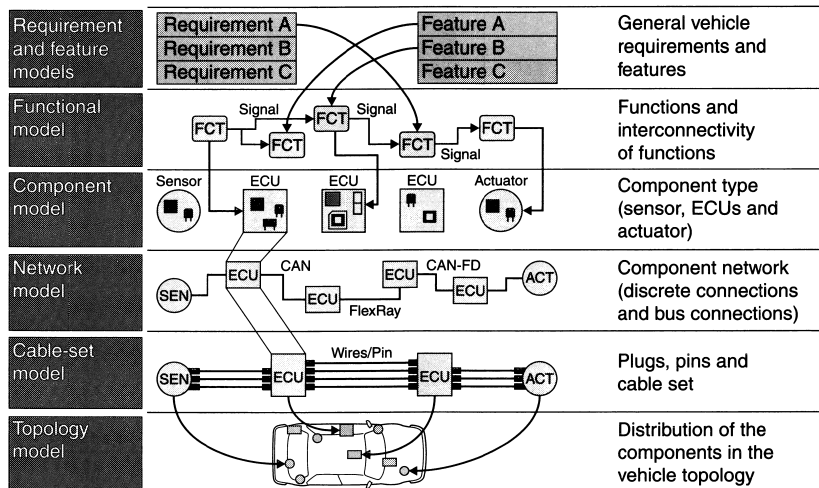
Functional model

Functional models are the preliminary stage of concrete technical systems. They describe the logic functions which are needed to realize the required performance features without going into their concrete technology. Thus the functional architecture is independent of the technical architecture. It is thereby possible to develop features optimally and without technical restrictions. For the example of ACC Stop-and-Go (Figure 9) this entails a breakdown into logic functions such as:

- Sensor technology,
- Longitudinal control of braking deceleration,
- Longitudinal control of acceleration,
- Actuator technology.

Figure 8: Models of E/E architecture

FCT Function, ECU Electronic Control Unit,
SEN Sensor, ACT Actuator.



Component model

Technology model

The technology model describes what technical realization is used for the specified transfer elements without already combining these into modules, such as electronic control units (ECUs). "Technology blocks" are created.

Thus, signal filtering can be realized with discrete components by means of a digital circuit or filter software on a microcontroller. Even a controller function can be executed with a discrete electronic circuit or a microcontroller. Voltage stabilization can be achieved by either a smoothing capacitor or a DC/DC converter.

The decision as to a technical implementation is influenced not only by the function, but also by further criteria such as costs, weight, scalability, etc. Before the technology blocks are combined into modules in the form of ECUs, the first step is to look for synergy with the further technology blocks to be integrated. A technological active chain is created (Figure 10). If a specific sensor technology is available, for example, for an active-chain link whose signal is required by another

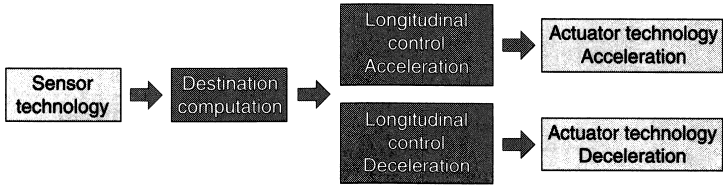
active chain, this will also be used. This occurs even if this sensor is overspecified for the additional user, i.e. there are lower requirements, for example, of the available signal range or of the accuracy.

It is nevertheless important to store the original requirement in a database as this synergy may no longer be present in another vehicle. The automotive industry usually uses the nomenclature according to DIN EN 60617 [3] to describe the hardware.

Node model

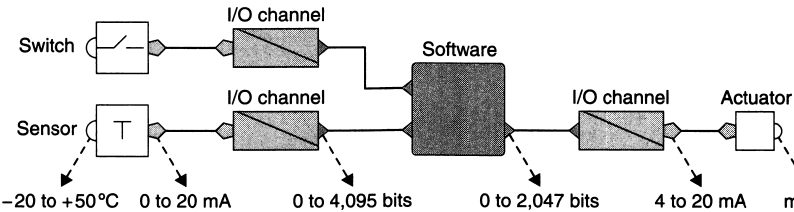
The links of the technological active chains are combined into groups at different locations, the "nodes". Here, strict adherence to the optimum cost and further criteria (e.g. latencies) is maintained in relation to integrating the technology blocks. Thus, attempts are made, for example, to integrate the software parts of several technological active chains on a common microcontroller. Sensor information is used jointly wherever possible and actuators are activated by different functions. For example the ACC and ESC functions activate the brake actuator.

Figure 9: Functional model ACC



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Figure 10: Example of a technological active chain



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Hardware model of the electronic component

This model represents the structure of the electronic hardware of an individual ECU. It is created by allocating specific electronic components from the technological active chains to an electronic module in a node. An ECU is therefore, generally speaking, a collecting point for electronic components of different systems, an "integration platform".

Software for controlling different systems from different sources (car manufacturers or their suppliers) is integrated on the microcontrollers located in the ECU. By networking the ECUs, it is possible to implement complex distributed functions which utilize sensors and actuators from different installation locations in the vehicle.

During development, initially customary circuit diagrams will be used for the electrical or electronic parts of the ECU. Then the ECU mechanics and the design and connection technology will be established. E/E-architecture development is confined to a very rough representation in the early concept phase.

Software model of the electronic component

The AUTOSAR standard defines the structuring of software close to hardware level and its interface to the application functions and establishes interfaces between application functions. AUTOSAR additionally defines standardized exchange formats which are supported by popular modeling tools (see AUTOSAR).

Typically, a distinction is made between basic and application software. Blocks of basic software are, for example, device-driver software, communication software, operating system, and hardware abstraction.

Network model

Network model of communication

Because all the technology blocks of a vehicle have been allocated to ECUs in the previous steps, a network of these ECUs is now in place with their communication relationships. The network model of communication represents all the ECUs in the motor vehicle which have bus communi-

cation and are thus directly or indirectly networked with each other (see for example Figure 1).

Each signal which is exchanged between two or more ECUs is assigned to a suitable bus system. AUTOSAR defines for this purpose standardized exchange formats which enable bus communication to be described.

Network model of energy supply

The allocation of the technology blocks to ECUs and sensor and actuator modules has also given rise to a network of electrical loads/consumers which requires a suitable energy supply. On the one hand, it is important to fuse individual electric circuits so that a short-circuit does not affect the entire network. On the other hand, not all circuits should be supplied with electrical energy in each operating state. The principle of "terminals" was therefore introduced for this purpose. Thus, for example, terminal 15 is only supplied with electrical energy when the ignition is switched on. The assignment of the individual terminals to ECUs follows the "terminal concept". Among others, the different vehicle states (e.g. driving, parking, loading, etc.) are required as input for the terminal concept. For example, parts of the energy management and the wake-up and go-to-sleep sequences of the ECUs are realized in the network by means of hardware.

The electrical circuit diagram (Figure 11) shows the electrical networking and fusing of the individual modules without the installation position being taken into consideration. Here the colors of the cables (not shown in the figure) and the matching with a terminal or fuse can be seen. The terminal designations follow the conventions in DIN 72552 [4].

The positive pole of the supply voltage is usually featured in the top half of the representation while the negative pole (ground) is featured in the bottom half.

Cable-set and topology models

This model groups electrical and electronic modules in a specific location in the vehicle (Figure 12). In this way, the connecting cables between the ECUs and the energy-supply leads of the electrical

loads/consumers are brought together in cable looms. This creates the cable set. Here many different boundary conditions must be observed, such as for example:

- the manufacturing concept (one-part or multi-part cable set),
- the loom cross-sections (flexibility),
- the electromagnetic compatibility (EMC),
- the heat dissipation,
- the weight,
- the costs (e.g. of copper),
- and the structure of the cable set in the vehicle.

The topology describes the possible routing paths in the body, such as for example the H structure, which consists of two main connections from the front end to the rear end of the vehicle and a cross cable (crossing) from the left to the right side of the vehicle.

Two-dimensional models are usually sufficient in the concept phase of a vehicle; detailed three-dimensional models are used in the later development phase.

E/E architecture development process

The E/E architecture development process links the individual draft stages with each other on a logic and time basis and provides quality criteria at the beginning and the end of a draft stage. The individual draft stages are described below.

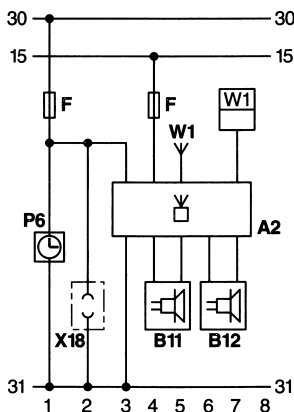
Requirement management

The requirements decisively determine the decisions of the E/E architect. It is advisable and common to distinguish between functional and non-functional requirements. Functional requirements refer to the desired performance features, the features, which can be used in the vehicle. Non-functional requirements refer to the technical solution and are therefore also known as draft restrictions.

Such a restriction can be, for example, the space available in the center console for installing ECUs. Another restriction can be the maximum permissible heat dissipation in a location which influences the power electronics positioned there.

Figure 11: Circuit diagram using example of a vehicle radio

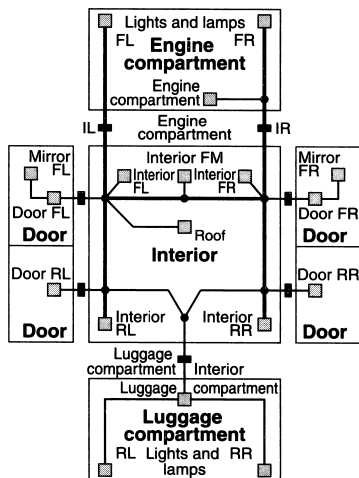
15, 30, 31 Terminal designations,
A2 Vehicle radio, W1 Vehicle antenna, F Fuse,
B11, B12 Speakers, P6 Timer,
X18 Diagnosis socket,
1 to 8 Section identification.



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Figure 12: Example of a two-dimensional space model

RL rear left, RR rear right,
FL front left, FR front right,
FM front middle, IL inside left,
IR inside right.



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Thus, for example, the audio amplifier in vehicles is frequently installed in the luggage-compartment area since the heat in the vehicle passenger compartment cannot be adequately dissipated.

Once the documentation of the functional and non-functional requirements has been completed, the actual development of the E/E architectures begins.

Development of E/E architectures

The development of the E/E architecture can follow two paths: The bottom-up approach, which starts out from existing components, and the top-down approach, which features the implementation of all the previously described modeling steps starting out from the functional and non-functional requirements.

In the bottom-up approach the creation of the E/E architecture starts out from the functionality of existing components and this is supplemented additionally by function and communication aspects. This approach is typically chosen for the creation of E/E architectures of successor generations to existing vehicle platforms or if cost restrictions necessitate the use of cost-effective components already existing on the market.

The top-down approach focuses on the function complexity and is typically chosen for creating E/E architectures of new vehicle platforms. In addition, the functional model will in future play an increasingly more important role, particularly to be able to realize cross-domain features. The functional model will be developed independently of the further technical implementation of the E/E architecture.

The use of E/E concept tools allows an exchange of data with development partners for electronic components or for the cable set.

Evaluation of models

The following must be observed for all approaches: During the transition from one model hierarchy to the next (e.g. from the functional model to the technology model), a list of evaluation criteria (e.g. reuse or testability) is compared with a portfolio of specimen solutions (e.g. bus technologies). Evaluation of the specimen solutions using the criteria allows

a solution to take shape on the basis of the purely functional requirements and irrefutable boundary conditions ("MUST criteria").

An alternative procedure consists in comparing a reference solution (e.g. the previous networking model) using the evaluation criteria with alternative solutions. This does indeed deliver fast results, but possibly not the global optimum.

Because the evaluation criteria are generally weighted differently by the car manufacturers, the electronic systems of the vehicles sometimes differ considerably from each other.

E/E architecture development tools

Ideally a tool is used for architecture modeling which can represent and network with each other the different models and model levels of the E/E architecture work. Fully connected documentation is created in this way. This enables the different disciplines involved in the development process to come on board at the relevant points. It should furthermore be possible to record the modeling properties numerically in order to be able to provide them with an evaluation.

Different E/E architecture development tools have in the meantime come onto the market which enable architecture modeling to be performed on a tool-assisted basis. An important point is the standardization of the models and their data formats. Only this facilitates competition between the tool manufacturers and opens up to the different disciplines involved the opportunity of joining the process at different points.

Summary and outlook

As a result of the ever increasing scope and the increasing networking of electronic systems, it is necessary to use suitable processes, methods and tools in E/E architecture development. E/E architecture development has established itself as an independent area of responsibility in the automotive industry and has a decisive influence in the development of new vehicles. It is thereby possible also to render further features in the automobile. These include for example highly automated driving functions like highway pilot or wireless software and firmware updates via the air interface (over the air). It is possible through new approaches in E/E architecture development to deliver powerful and reliable E/E architectures in the future as well. If the procedures described in this publication are consistently applied and developed further, the increasing complexity in motor vehicles will also be manageable in the future and will continue to make significant contributions to improving traffic flow, traffic safety, driving comfort, and economical fuel utilization.

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- [2] Automated driving, electrification and connectivity – the evolution of vehicle motion control. Alexander Häußler, Robert Bosch GmbH (DOI 10.1007/978-3-658-09711-0_3).
- [3] DIN EN 60617: Graphical symbols for diagrams.
- [4] DIN 72552: Terminal markings for motor vehicles.

Automotive sensors

Basic principles

Function

Sensors convert a physical or a chemical (usually non-electrical) quantity Φ into an electrical quantity E . This is often also done via further, non-electrical intermediate stages.

Figure 1: Types of characteristic curve

S Output signal,

X Measured variable.

a) Continuous, linear,

b) Continuous, nonlinear,

c) Discontinuous, multistage,

d) Discontinuous, dual-stage with hysteresis.

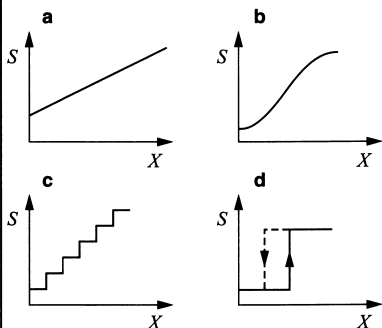


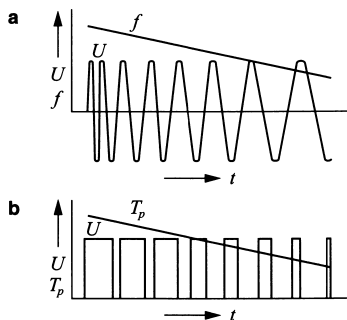
Figure 2: Signal shapes (examples)

a) Frequency f ,

b) Pulse duration T_p ,

U Output signal,

t Time.



Sensor classification

Sensors can be classified according to very different standpoints. With regard to their use in motor vehicles, they can be categorized as follows.

Assignment and application

- Functional sensors (e.g. pressure sensor, temperature sensor, air-mass sensor), primarily for open- and closed-loop control functions.
- Sensors for safety (passenger protection: airbag and driving-dynamics control) and protection (theft deterrence).
- Sensors for vehicle monitoring (onboard diagnostics, consumption and wear quantities) and for providing information to driver and passengers.

Type of characteristic curve

- Continuous linear characteristic curves (Figure 1a) are used particularly for control functions across a broad measurement range. Linear characteristic curves furthermore have the advantage that they are easy to check and adjust.
- Continuous nonlinear characteristic curves (Figures 1b) are often used for closed-loop control of a measured variable within a very narrow measurement range (e.g. control of the air/fuel ratio at $\lambda = 1$, control of the compression level).
- Discontinuous dual-stage characteristic curves, with hysteresis in some cases (Figure 1d) are used to monitor limit values where an easy remedy is possible when they are reached. If remedy is more difficult, early warning can be effected at an earlier stage by means of multiple stages (Figure 1c).

Type of output signal

Analog output signal (Figure 2a):

- Current or voltage, or corresponding amplitude,
- Frequency or period duration,
- Pulse duration or pulse duty factor.

Discrete output signal (Figure 2b):

- dual stage (binary encoded),
- multistage – irregular graduation (analog encoded),
- multistage – equidistant (analog or digital encoded).

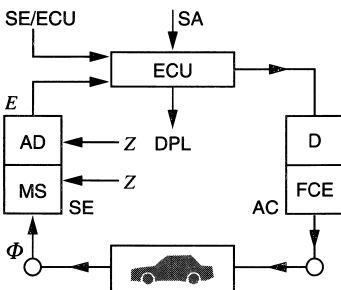
Continuous signals are constantly available at the sensor output, discontinuous signals are available only at discrete times. A bit-serially output signal is inevitably discontinuous.

Automotive applications

In their function as peripheral elements, sensors and actuators form the interface between the vehicle with its complex drive, braking, chassis, suspension, and body functions (including guidance and navigation functions), and the usually digital-electronic control unit (ECU) as the processing unit (Figure 3). An adapter circuit is generally used to convert the sensor's signals into the standardized form (measuring chain, measured-data registration system) required by the ECU. In addition, system operation can be influenced by sensor information from other processing elements for example via bus systems and/or by driver-operated switches.

Figure 3: Automotive sensor

Φ Physical quantity,
 E Electrical quantity,
 Z Disturbance.
 AC Actuator,
 AD Adapter circuit,
 DPL Display,
 MS Measuring sensor,
 SA Switch,
 SE Sensor,
 ECU Electronic control unit,
 FCE Final controlling element,
 D Driver.



Main requirements

Operating conditions

Automotive sensors are sometimes exposed to extreme conditions in their installation locations. These are mechanical stresses (e.g. vibrations and impacts), climatic influences (e.g. low and extremely high temperatures, moisture), chemical influences (e.g. splash water, salt spray, fuel, engine oil, battery acid), and electromagnetic influences (e.g. high-frequency interference, mains-borne interference pulses, overvoltage). The degree of stress to which a sensor is subjected is determined by the operating conditions at its installation location.

Reliability

According to application and technical requirements, automotive sensors are assigned to one of three reliability classes:

- Steering, brakes, passenger protection,
- Engine, drivetrain, suspension, tires,
- Comfort and convenience, information, diagnosis, theft deterrence.

Size

The constantly increasing number of electronic systems in vehicles on the one hand and the ever more compact shape of vehicles on the other hand force engineers to adopt extremely small designs. In addition, the pressure of increased fuel economy necessitates a consistent reduction of vehicle weight. Various miniaturization concepts are employed to achieve compact sensor dimensions:

- Substrate and hybrid technologies (e.g. for strain-dependent resistors, thermistors, and magnetoresistors),
- Semiconductor technology (e.g. for Hall-effect crankshaft sensors),
- Surface and bulk micromechanics (e.g. for silicon pressure, acceleration, and yaw sensors),
- Microsystem technology (integration of micromechanical or microoptical components with microelectronic circuits in a complex system).

Manufacturing costs

Electronic systems in vehicles contain up to 150 sensors. This abundance of sensors forces engineers to radically reduce costs compared with other areas of use.

Extensively automated manufacturing processes working at great efficiency levels are used. In other words, each process step is always performed simultaneously for a larger number of sensors. The manufacture of semiconductor sensors typically involves the simultaneous integration of 100 to 1,000 sensors on one silicon wafer. The automotive industry's huge demand for sensors has set new standards here.

Accuracy requirements

The accuracy requirements for automotive sensors are lower than for sensors for the process industry for example. The permissible deviations are generally greater than 1 % of the upper range value of the measurement range. The inevitable influences of aging must also be taken into consideration here.

However, ever more sophisticated and complex systems call for higher levels of accuracy. This can be achieved to a certain extent by reducing the manufacturing tolerances and by improving the adjustment and compensation technologies. "Integrated sensors" provide for a significant advance here.

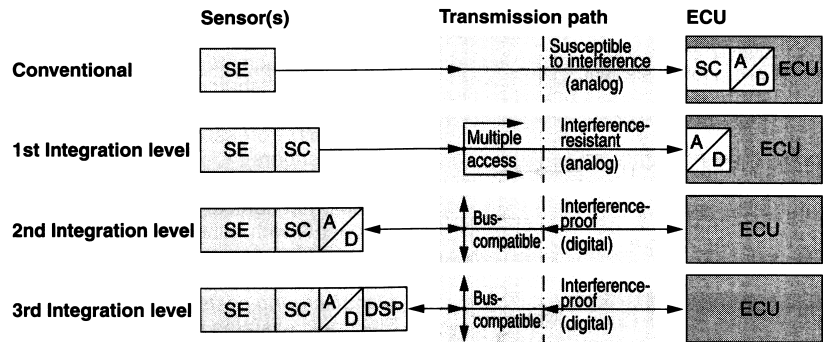
Integrated sensors

Systems range from hybrid and monolithic integrated sensors and electronic signal-processing circuits at the measuring point, through to complex digital circuits, such as analog-digital converters and microcomputers, for complete utilization of the sensor's inherent accuracy ("intelligent" sensors, Figure 4). These systems offer the following benefits and options:

- Reduction of load on the ECU,
- Uniform, flexible, bus-compatible interface,
- Multiple application of sensors,
- Multisensor designs,
- Use of small measuring effects and high-frequency measuring effects (local amplification and demodulation),
- Correction of sensor deviations at the measuring point, and common calibration and compensation of sensor and circuit, are simplified and improved by storage of the individual correction information in semiconductor memory chips (e.g. PROM).

Figure 4: Sensor integration levels

SE Sensor,
SC Signal conditioning (analog),
AD Analog-digital converter,
ECU Electronic control unit,
DSP Digital signal processing.



Micromechanics

Applications

Micromechanics is defined as the application of semiconductor technology in the production of mechanical components from semiconductor materials (usually silicon). This type of application exploits both the semiconducting and the mechanical properties of silicon. The first micro-mechanical silicon pressure sensors were installed in motor vehicles at the beginning of the 1980s. Typical mechanical dimensions can extend into the micrometer range.

The mechanical properties of silicon (e.g. strength, hardness and modulus of elasticity, see Table 1) can be compared to those of steel. However, silicon is significantly lighter and has greater thermal conductivity than steel. Single-crystal silicon wafers are used with almost perfect mechanical properties. Hysteresis and creepage are negligible. Due to the brittleness of the single-crystal material, the stress-strain curve has no plastic range; the material ruptures when the elastic range is exceeded.

Two methods of manufacturing micro-mechanical structures in silicon have established themselves: volume micromechanics (VMM) and surface micromechanics (SMM). Both methods use the

standard procedures of microelectronics (e.g. epitaxial growth, oxidation, diffusion, and photolithography) together with some additional special procedures [1].

Volume micromechanics

The silicon wafer material is processed at the required depth using anisotropic (alkaline) etching with or without an electrochemical etching stop. From the rear, the material is removed from inside the silicon layer, where there is no etching mask resting on top (Figure 5). Using this method, very small membranes can be produced with typical thicknesses of between 5 and 50 μm , as well as openings, beams and webs as are needed for instance in pressure and acceleration sensors.

The problem when etching with alkaline media lies in the fact that the walls run inwards at an angle. In order to be able to effect high-precision etching at depth with vertical walls, it was necessary to develop a new process. Here Bosch made a breakthrough with the development of the DRIE process (Deep Reactive Ion Etching), which has in the meantime come to be known generally in the industry as the "Bosch process". This involves the creation in a special gas-phase reactor of alternating gases and accompanying conditions for an etching

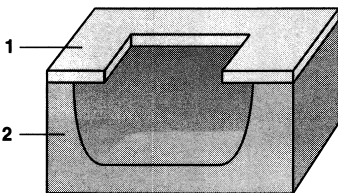
Table 1: Mechanical properties of silicon

Quantity	Unit	Silicon	Steel (max.)	Stainless steel
Tensile load	10^5 N/cm^2	7.0	4.2	2.1
Knoop hardness	kg/mm^2	850	1,500	660
Modulus of elasticity	10^7 N/cm^2	1.9	2.1	2.0
Density	g/cm^3	2.3	7.9	7.9
Thermal conductivity	$\text{W/cm} \cdot \text{K}$	1.57	0.97	0.33
Thermal expansion	$10^{-6}/\text{K}$	2.3	12.0	17.3

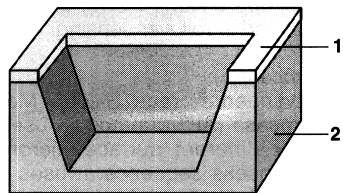
Figure 5: Electrochemical etching

a) Isotropic (in acid etching media), b) Anisotropic (in alkaline etching media).
1 Etching mask (e.g. oxide or nitride), 2 Silicon.

a



b



stage and then a passivation stage. This etching and the subsequent passivation of the walls are set such that very precise vertical walls are created. This process can be used for both volume and surface micromechanics.

Surface micromechanics

In contrast to volume micromechanics, surface micromechanics merely uses the silicon wafer as the substrate. Moving structures are usually formed from polycrystalline silicon layers which, similarly to a manufacturing process for integrated circuits, are deposited on the surface of the silicon by epitaxial growth.

When a surface-micromechanical component is made, a sacrificial layer of silicon oxide is first applied on the wafer and structured with standard semiconductor processes, i.e. partly removed again specifically (Figure 6a). An approx. 10 µm thick polysilicon layer (epipoly layer) is then applied at high temperatures in an epitaxial reactor (Figure 6b) and whose desired structure is anisotropically, i.e. vertically, etched with the aid of a lacquer mask (deep etching or trenching, Figure 6c). The vertical side walls are obtained with the Bosch process by alternating etching and passivation cycles. After an etching cycle, the etched side-wall section is provided during passivation with a polymer as protection so that it is not attacked during the subsequent etching. Vertical side walls with a high representation accuracy are created in this way. In the last process stage (Figure 6d) the sacrificial layer beneath the polysilicon layer is removed with gaseous hydrogen fluoride in order to expose the structures (Figure 7).

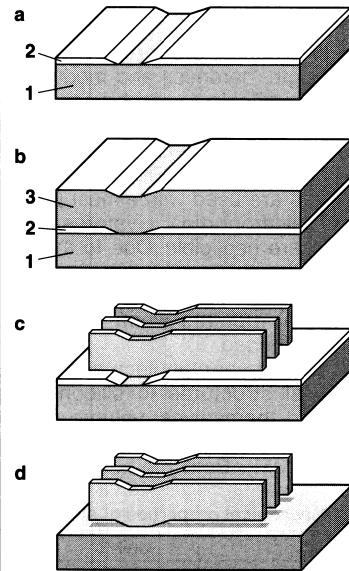
Among other things, surface micromechanics is used in the manufacture of capacitive acceleration sensors for airbag systems and in the manufacture of yaw sensors for applications in driving-dynamics control and in rollover sensing.

APSM process

The "Advanced Porous Silicon Membrane" process (APSM process) uses a completely different surface-micromechanical process sequence. It uses the properties of porous silicon to create

Figure 6: Process stages in surface micromechanics

- Depositing and structuring the sacrificial layer,
 - Depositing polysilicon,
 - Structuring polysilicon by deep etching,
 - Removing the sacrificial layer and so producing freely moving structures on the surface.
- Silicon,
 - Oxide layer (sacrificial layer),
 - Polysilicon layer ("epipoly").

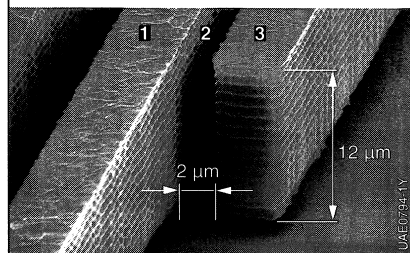


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Figure 7: Structure of a surface-micromechanical sensor

Recording with scanning electron microscope.

- Fixed electrode,
- Gap,
- Spring electrode.



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beneath a monocrystalline membrane an exactly defined cavity in which a vacuum is enclosed.

The core of the APSM process is porous silicon. This can be manufactured selectively and on a locally limited basis in *p*-doped silicon in an electrochemical anodizing process in hydrofluoric acid. In this process some of the silicon is dissolved out of the crystal to leave a porous, sponge-like silicon shell, the "porous silicon".

Porous silicon in turn can be rearranged at high temperatures. The silicon shell dissolves and forms under suitable conditions a thin membrane on the surface. A cavity forms below this membrane (Figure 8). This thin membrane can be enlarged to the target thickness by means of epitaxial growth.

The monocrystalline epitaxial layer is used for example as the diaphragm of a pressure sensor. Evaluating-circuit elements in the epitaxial layer outside the diaphragm provide for a high-precision, small and inexpensive pressure sensor.

Modern pressure sensors, e.g. barometric pressure sensors for engine-management systems, are manufactured using the APSM process.

Wafer bonding

In addition to structuring the silicon, joining two wafers represents another essential task in micromechanical production engineering. Joining technology is required, for example, in order to hermetically seal a reference-vacuum chamber (e.g. for pressure sensors), to protect sensitive structures by applying caps (e.g. in acceleration and yaw sensors, Figure 9), or to join the silicon wafer with intermediate layers which minimize the thermal and mechanical stresses (e.g. glass base on pressure sensors).

In the case of anodic bonding, a Pyrex-glass wafer is joined to a silicon wafer at a voltage of some 100 V and a temperature of approx. 400 °C (Figure 10). A strong electrostatic attraction and an electrochemical reaction (anodic oxidation) result in a permanent hermetic bond between the glass and the silicon.

In the case of seal-glass bonding, two silicon wafers are contacted by way of a glass-solder layer applied in a

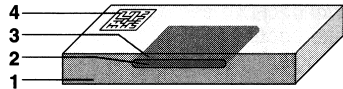
screen-printing process at approx. 400 °C and under the exertion of pressure. The glass solder melts at this temperature and produces a hermetically sealed bond with the silicon.

References for Sensors – Basic principles

[1] U. Hilleringmann: Mikrosystemtechnik – Prozessschritte, Technologien, Anwendungen. B.G. Teubner-Verlag, Wiesbaden 2006.

Figure 8: Creating exact vacuum caverns in silicon with the APSM process

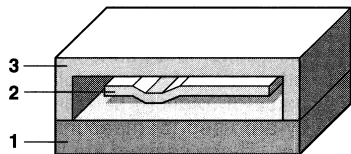
- 1 Silicon,
- 2 Cavity, created from porous silicon by the APSM process,
- 3 Membrane,
- 4 Evaluating circuit.



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Figure 9: Thin-layer cap for hermetically sealing e.g. an acceleration sensor

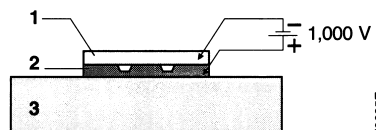
- 1 Silicon,
- 2 Freely moving structure,
- 3 Cap.



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Figure 10: Anodic wafer bonding

- 1 Pyrex glass,
- 2 Silicon,
- 3 Heating plate ($T \approx 400\text{ °C}$).



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Position and angular-position sensors

Measured variables

These sensors record one- or multidimensional displacement and angle positions (translational and rotatory variables) of the most varied types and ranges. Examples of such measured variables are:

- Accelerator-pedal position for recording the torque request for engine management (driver command),
- Throttle-valve position for controlling the throttle valve,
- Fuel-tank level,
- Steering-wheel angle,
- Position of the transmission selector lever for electronic transmission control
- Seat position,
- Mirror position,
- Control-rack position in the diesel in-line fuel-injection pump,
- Travel of clutch servo unit,
- Brake-pedal position,
- Tilt angle.

In this sector of applications, activities have long since been directed at changing over to proximity or non-contacting sensor principles. Such sensors are wear-free and thus have a longer service life as well as being more reliable. The costs involved though, often force vehicle manufacturers to retain the “wiper-type” sensor principle, and such sensors still perform efficiently enough for many measurement purposes.

In practice, incremental sensor systems are also often referred to as angular-position (or angle-of-rotation) sensors, even when they are used for measuring rotational speed. These sensors are in reality not angular-position (or angle-of-rotation) sensors. Since the increments (steps with which a given quantity increases) which have to be measured with these sensors in order to measure the deflection angle must first be counted with the correct preceding sign (in other words, added), there is the possibility of permanent interference.

Wiper potentiometer

Measurement principle

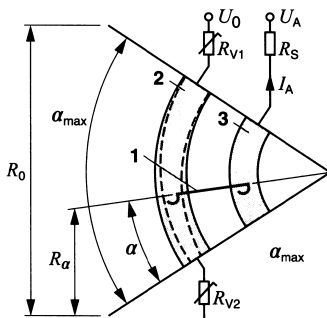
The wiper potentiometer – usually designed as an angular-position sensor – measures travel by exploiting the proportional relationship between the length of a wire or film resistor (conductor track made of cermet or “conductive plastic”) and its electrical resistance (Figure 1). At present, this is the lowest-priced travel and angular-position sensor.

To protect against overloading, supply voltage is usually applied to the measurement track through series resistors R_V . These resistors can also be used for calibration of zero point and curve slope. The shape of the contour across the width of the measurement track (including that of individual sections) influences the shape of the characteristic curve.

The standard wiper connection is furnished by a contact track consisting of the same material mounted on a low-resistance substrate. Wear and measurement distortions can be avoided by reducing the current at the pick-off ($I_A < 1 \text{ mA}$) and sealing the unit against dust and liquid. Also essential to minimizing wear is to have an optimum friction pairing of wiper

Figure 1: Wiper potentiometer

- 1 Wiper,
 - 2 Potentiometer track (measurement track),
 - 3 Contact track.
- U_0 Supply voltage,
 U_A Measurement voltage,
 I_A Wiper current,
 R_0 Resistance of measurement track,
 R_α Resistance of part of measurement track,
 R_V Series resistors, R_S Protective resistor,
 α Measurement angle.



and potentiometer track; here wipers can have a spoon or scraper shape and have a single or multiple design, even in the shape of a broom.

The wiper potentiometer together with further resistors form a voltage divider (Figure 2). The picked-off voltage is a measure of the wiper position.

Advantages of the potentiometer are, for example, the low costs, the simple and clear design, the large measuring effect (measuring stroke corresponds to the supply voltage), the wide operating-temperature range up to 250 °C, and the high degree of accuracy (better than 1 % of the upper range value of the measurement range).

Disadvantages of the potentiometer are, for example, mechanical wear caused by abrasion, measuring errors caused by abraded remnants, wiper lift-off in the event of vibrations, and the limited miniaturization capability.

Wiper-potentiometer applications

Throttle-valve angle sensor

Mounted on the throttle valve in a gasoline engines is a throttle-valve sensor (Figure 3), which signals the position of the

throttle valve to the engine-management system. The throttle-valve angle sensor has a redundant design for diagnostic purposes (Figure 2). This makes available two independent signals which can be checked for plausibility against each other. Redundant measurement enables faults to be detected.

Accelerator-pedal sensor

The accelerator-pedal (pedal-travel) sensor senses the travel or the angle of the pressed accelerator pedal. The engine-management system interprets this value as a torque request from the driver. The accelerator-pedal sensor is integrated together with the accelerator pedal in the accelerator-pedal module. With these units that are ready for installation there is no need for adjustment on the vehicle.

With the potentiometric sensor design the measurement signal is generated by a potentiometer. The engine ECU converts the measured voltage using the stored sensor curve into the covered pedal travel or into the accelerator pedal's angular position.

Like the throttle-valve sensor the accelerator-pedal sensor has a redundant design. One sensor version operates with a second potentiometer that always delivers half the voltage of the first potentiometer at all operating points. Two independent

Figure 2: Electrical circuit of throttle-valve sensor

- 1 Throttle valve,
 - 2 Throttle-valve sensor.
- U_A Measurement voltages,
 U_V Operating voltage,
 R_1, R_2 Potentiometer tracks 1 and 2,
 R_3, R_4 Trimming resistors,
 R_5, R_6 Protective resistors.

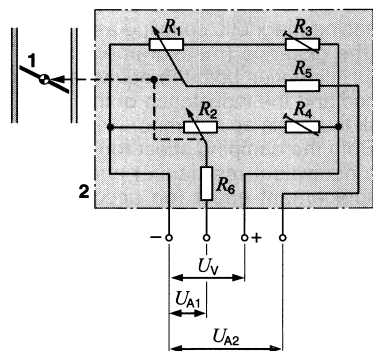
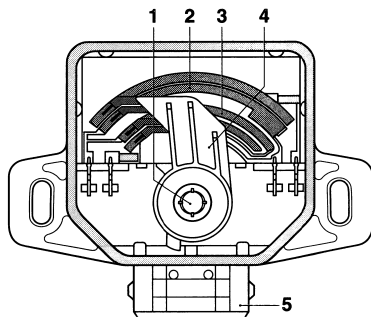


Figure 3: Throttle-valve sensor

- 1 Throttle-valve shaft,
- 2 Potentiometer track 1,
- 3 Potentiometer track 2,
- 4 Wiper arm with wipers,
- 5 Electrical connection.



signals are thus available for the purpose of fault detection. Sensor versions with low-idle switches were also customary in the past; the state of these sensors had to be plausible with the measurement signal of the potentiometer.

A further switch for detecting a kick-down can be integrated in the accelerator-pedal module of vehicles with automatic transmissions. Alternatively, this signal can be derived from the rate of change of the potentiometer voltage or generated when a threshold value is exceeded.

Fuel-level sensor

The level in the fuel tank is transmitted by the float via the float lever to the potentiometer (Figure 4). Firstly, the prepared measured value is transmitted for display

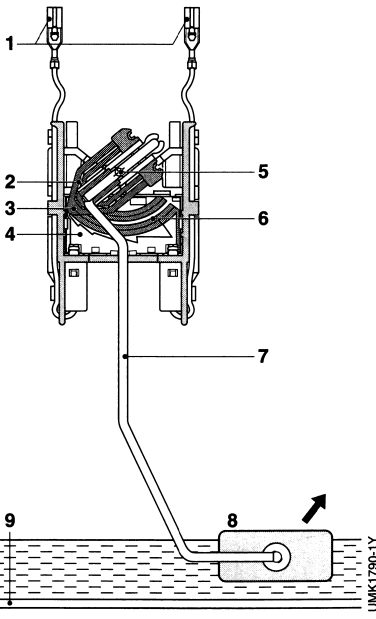
in the instrument cluster; secondly, the fuel level is used to measure fuel consumption (e.g. for displaying the range calculated by the on-board computer).

Magnetically inductive sensors

Of all the sensors which perform non-contacting position measurement, magnetic sensors are particularly non-susceptible to interference and robust. This applies in particular to those principles relying on alternating current, in other words magnetically inductive principles. Compared with a micromechanical sensor though, the coil configuration needed here requires far more space. This means therefore that there is no favorable possibility of redundant (parallel measurement) design.

Figure 4: Potentiometric fuel-level sensor

- 1 Electrical connections,
- 2 Wiper spring,
- 3 Contact rivet,
- 4 Resistor board,
- 5 Bearing pin,
- 6 Twin contact,
- 7 Float lever,
- 8 Float,
- 9 Base of fuel tank.



Measurement principle, short-circuiting-ring sensors

Of all the established principles of magnetically inductive sensors it is mainly short-circuiting-ring sensors that have up to now been used by Bosch in motor vehicles. These sensors sense for example the control-rack position in diesel in-line fuel-injection pumps [1]. However, these are no longer used in a macromechanical design form for new developments.

Measurement principle, eddy-current sensors

When an electrically conducting disk (e.g. made of aluminum or copper) approaches a (usually air-core) coil supplied with high-frequency alternating current, eddy currents are created in the disk by the increasing magnetic coupling as a function of the distance (measurement travel s). This influences both the equivalent resistance and the inductance of the coil. The disk thus acts as a damper disk.

Both the damping effect (on account of the equivalent resistance) and the field-displacement effect (on account of the inductance) can be used to convert the measuring effect into an electrical output voltage. The suitable choice is in the first case for example an oscillator of variable amplitude and in the second case an oscillator of variable frequency or a constantly powered, inductive voltage divider.

A high operating frequency is required due to the low coil inductance. This necessitates a direct assignment of electronic circuitry to the sensor.

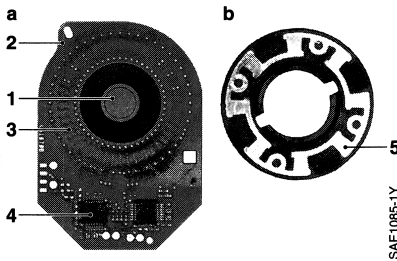
Application: Position sensor for transmission control

In automatic transmissions position sensors sense the position of final controlling elements (e.g. selector-lever shaft, selector valve or parking-lock cylinder). Because of the complex requirements from the different transmission topologies and the space and functional requirements different physical measurement principles (Hall, AMR, GMR and eddy-current principles) and types (linear and rotatory sensing) are used.

In the eddy-current sensor the rotor rotates with the selector-lever shaft (Figure 5). A return coil is mounted on the rotor. The fixed sensor board contains redundant transmitter and receiver coils with the associated evaluation electronics. The transmitter coil induces in the return coil an eddy current opposing its cause whose magnetic field induces a voltage in the receiver coil. The geometries of the return coil and the receiver coils are matched to each other in such a way that continuously variable rotor positions can be sensed. The rotatory position sensor thus determines the selector-lever positions P, R, N, D, 4, 3, and 2.

Figure 5: Position sensor using eddy-current principle

- a) Sensor board with protective circuit,
b) Rotor.
1 Selector-lever shaft,
2 Sensor board,
3 Redundant transmitter and receiver coils,
4 Redundant evaluation electronics,
5 Rotor with return coil.



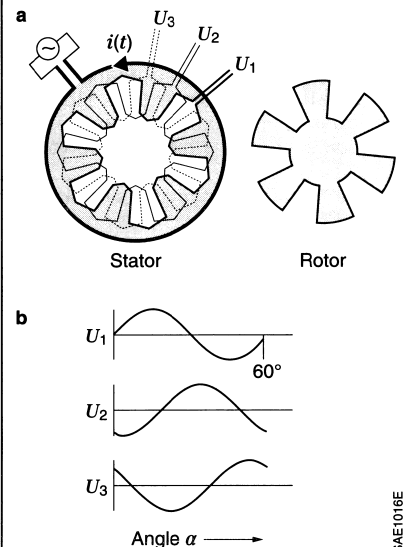
For safety reasons the sensor generates two independent, opposite signals which are checked for plausibility against each other.

Sensors with rotating alternating fields

Two- or multipole alternating-field structures can be arranged either in a circle or linearly with coils energized with alternating current of angular frequency Ω or coil-like configurations (such as meander conductor-track structures) (Figure 6). Compared with a usually fixed set of receiver coils, which have the same pole pitch, these pole structures with fixed pole pitch can be displaced by the movement of the system to be measured – whether it be rotatory or translational in nature. Here, the amplitudes of the receiver signals (U_1 , U_2 , U_3 , etc.) change sinusoidally with the movement. If the receiver coils are offset against each other by a certain part of the pole pitch T (e.g. $T/4$ or $T/3$), the sine shape is phase-displaced in each case by a corresponding angle (e.g. by 90° or 120°). After rectification, the angle

Figure 6: Sensor with rotating alternating fields

- a) Schematic layout,
b) Output signals.



of rotation to be measured can be calculated with great accuracy from these voltages. This is the mode of operation of the sensors referred to in classical metrology as synchro, resolver, or inductosyn processes, and preferably configured as angular-position encoders.

The angular-position sensor shown in Figure 6 most resembles the inductosyn process. This is a sensor with a six-figure pole structure ($n = 6$), which in electrical terms converts an angle of rotation of $\varphi = 60^\circ$ into a phase displacement of signal amplitudes of $\alpha = 360^\circ$. All the necessary conductor-track structures are at least in the case of the fixed part (stator) situated on multi-layer board material. The rotor part can also if necessary be designed as a stamping, either self-supported or mounted on plastic carriers (by hot stamping).

Situated on the stator is a circular conductor-track loop which, independently of the angle of rotation, induces at an operating frequency of 20 MHz an eddy current in a self-contained meander loop of roughly equal outside diameter on the rotor. Like the excitation loop, this eddy current creates a secondary magnetic field which overlaps the excitation field such that it attempts to damp it. If there were only a circular conductor track congruent to the stator loop on the rotor instead of the meander, this would simply extinguish the primary field to the greatest possible extent. However, the meander structure creates a resulting multipole field, which can be rotated

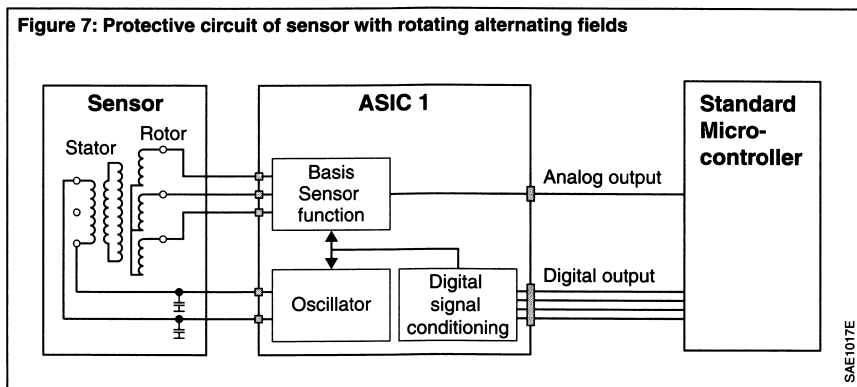
with the rotor and whose total flux is also virtually zero.

This multipole alternating field is sensed by concentric receiver coils (meanders) of identical shape likewise located on the stator. These coils or meanders are displaced within a pole pitch (of e.g. 60°) by $1/3$ in each case, i.e. electrically in their signal amplitude by 120° in each case (Figure 6b). However, the receiver coils stretch over all the n pole pairs (series connection) and utilize the sum total of all the pole fields.

Figure 7 shows the receiver coils star-connected. For the purpose of determining the electrical phase angle α (or the mechanical angle of rotation), the coil signals are routed to an ASIC, which performs the necessary rectification, selection, and ratio formation. The ASIC receives the necessary digital control signals from a nearby microcontroller. A different version of an ASIC is, however, also able to operate the sensor completely independently (stand-alone). The ASICs also permit an end-of-line adjustment of the mechanical and electrical tolerances in production.

For applications with increased safety requirements, it is also possible to design a redundant system with two isolated signal paths and two ASICs. The sensor principle can also be configured very advantageously in an "open" form as a travel sensor. The sensor can therefore be used at many points in a motor vehicle (e.g. recording the throttle-valve angle in the throttle device, lever position on auto-

Figure 7: Protective circuit of sensor with rotating alternating fields



matic transmissions, headlight position for headlight leveling control).

Magnetostatic sensors: Overview

Magnetostatic sensors measure a DC magnetic field. In contrast to the magnetically inductive sensors with coils, they are far more suitable for miniaturization and can be manufactured at reasonable cost using microsystem techniques. Since DC magnetic fields can easily penetrate through housing walls made of plastic but also of non-ferromagnetic metal, magnetostatic sensors have the advantage that the sensitive, generally fixed part can be well encapsulated and protected in respect of the rotatory part – usually a permanent magnet or a soft-magnetic conductive element – and in respect of the environment. Above all, galvanomagnetic effects (Hall and Gaussian effects) and magnetoresistive effects (AMR and GMR) are used.

Hall effect

The Hall effect occurs in thin semiconductor chips. If such a current-carrying chip is permeated vertically by a magnetic induction B , the charge carriers are deflected by the Lorentz force vertically to the field and to the current I by the angle α from their otherwise straight path. It is thus possible to pick off a voltage U_H proportional to the field B and to the current I transversally to the current direction between two opposing marginal points of the chip (Hall voltage, Figure 8):

$$U_H = \frac{R_H I B}{d}$$

where

R_H Hall coefficient,

d Chip thickness.

The coefficient R_H crucial to the measurement sensitivity of the chip is only comparatively small in the case of silicon. However, because the chip thickness d can be made extremely thin using diffusion techniques, the Hall voltage U_H attains a technically acceptable value again.

When silicon is used as the basic material, a signal-conditioning circuit can be integrated on the chip. Sensors using these principles are thus cheap to produce.

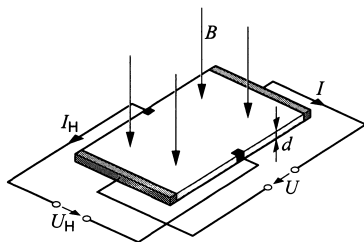
In terms of measurement sensitivity, temperature coefficient, and temperature range, however, silicon is by no means the best semiconductor material for Hall sensors. III-V semiconductors such as gallium arsenide or indium antimonide, for example, demonstrate better properties.

Gaussian effect

In addition to the transversally directed Hall effect, semiconductor chips are also subject to a longitudinal resistance effect, otherwise known as the Gaussian effect. Independently of the field direction the series resistance increases according to a roughly parabolic characteristic curve. Elements which utilize this effect are called magnetoresistors (Siemens trade name) and are manufactured from a III-V semiconductor, crystalline indium antimonide (InSb).

Figure 8: Hall effect

B Magnetic flux density,
 I Supply current,
 U Supply voltage,
 U_H Hall voltage,
 I_H Hall current.



Hall sensors

Hall switch

In the most simple case, in the Hall switch the Hall voltage is applied to an electronic threshold circuit integrated in the sensor (Schmitt trigger), which then outputs a digital signal. If the magnetic induction B applied at the sensor is below a given minimum threshold level, the Schmitt trigger's output value corresponds to a logical 0 (release status); if it exceeds a given upper threshold, the output value corresponds to a logical 1 (operate status). Since this behavior is guaranteed across the complete operating-temperature range and for all sensors of a given type, the two threshold values are relatively far apart (approx. 50 mT). In other words, it takes a considerable induction jump ΔB to trigger the Hall switch.

Such Hall sensors manufactured for the most part in bipolar technology are indeed very economical, but are at best only good for switch operation (e.g. Hall vane switches for triggering ignition in earlier ignition systems, digital steering-angle sensor). Hall vane switches are too inaccurate for recording analog variables.

Hall sensors using the spinning-current principle

A disadvantage of a simple Hall sensor is its simultaneous sensitivity to mechanical stresses (piezoelectric effect), which are inevitable due to packaging and result in an unfavorable offset temperature coefficient. This disadvantage has been overcome by the application of the spinning-current principle (Figure 9), combined with the transition to CMOS technology. The piezoelectric effect does arise here too, but is compensated by time averaging of the signal, since it occurs in the event of very fast, electronically controlled switching (rotation) of the electrodes with a different polarity sign.

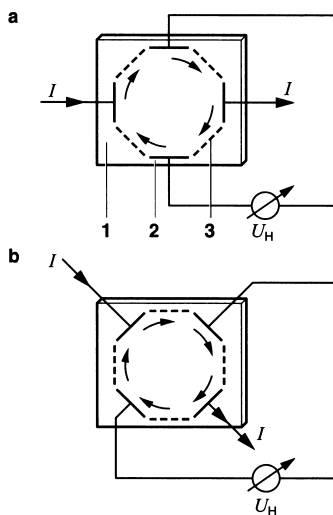
If the desired aim is to avoid the expense of complex electronics to switch the electrodes, it is also possible to integrate in close proximity several Hall sensors (two, four or eight) with correspondingly different alignment of the current path, and to add up their signals in the form of an averaging.

Only through these measures was it possible for Hall ICs to become well suited to analog sensor applications. These measures though barely resulted in a reduction of the sometimes considerable effects of temperature on the measurement sensitivity.

Such Hall ICs are suitable above all for the measurement of small travel distances, in which they register the fluctuating field strength of a permanent magnet as it approaches (used for example in the force sensor for sensing front-passenger weight). Up to then, similarly good results could only be achieved by the use of individual Hall elements of, for example, III-V semiconductors (e.g. GaAs) with a hybrid downstream amplifier.

Figure 9: Hall sensor using the spinning-current principle

- a) Rotation phase φ_1 ,
- b) Rotation phase $\varphi_2 = \varphi_1 + 45^\circ$.
- 1 Semiconductor chip,
- 2 Active electrode,
- 3 Passive electrode.
- I Supply current,
- U_H Hall voltage.



Applications of Hall sensors

Position sensors

for transmission control

In this type of position sensor for transmission control for linear position sensing four Hall switches are arranged on a printed-circuit board in such a way that they sense the magnetic encoding of a linearly displaceable multipolar permanent magnet (Figure 10). The magnet carriage is coupled to the linearly actuated selector valve (hydraulic valve in the transmission control plate) or the parking-lock cylinder.

The position sensor senses the positions of the selector valve (P, R, N, D, 4, 3, 2) and the intermediate ranges and outputs these in the form of a 4-bit code to the transmission-control system. For safety reasons the encoding of the position is configured as a single step. In other words, two bit changes are always required until a new position is detected. The sequence of these bit changes corresponds to a Gray code.

Axle sensors

Axle sensors sense the body's inclination angle that changes as a result of vehicle load or during braking and acceleration. The range of the headlamps can be adapted to the conditions with this

information (automatic headlamp leveling control).

Vehicle inclination is measured by angle-of-rotation sensors (axle sensors). These are mounted to the body at the front and rear. Compression is measured by a rotary lever which is connected via a pushrod to the vehicle axle. The vehicle inclination is obtained from the difference between the sensor signals on the front and rear axles.

The axle-sensor stator (Figure 11) incorporates a Hall element located in the ring magnet's homogeneous field. The magnetic field induces in the Hall element a Hall voltage that is proportional to the magnetic field strength. During compression the axle-sensor shaft rotates with the ring magnet, and thus the magnetic field is also altered by the Hall element. The Hall element delivers a signal that is dependent on the angle of rotation of the shaft and thus on the compression travel.

Accelerator-pedal sensors

Using a rotatable magnetic ring ("movable magnet"), together with a number of fixed

Figure 10: Encoding of position sensor for transmission control

a) Magnetic encoding,

b) Position ranges.

1 Moving carriage,

2 Fixed position of Hall elements.

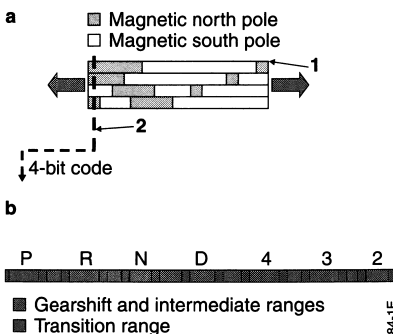


Figure 11: Axle sensor

1 Rotary lever,

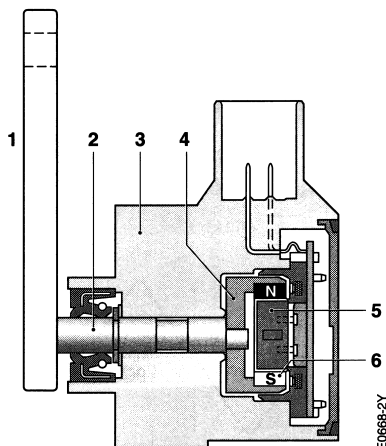
2 Shaft,

3 Housing,

4 Ring-magnet mounting,

5 Stator with Hall IC,

6 Ring magnet.



soft-magnetic conductive elements, a linear output signal can be generated for a larger angular range without conversion being necessary (Figure 12). Here, the movable magnet's bipolar field is directed through a Hall sensor located between semicircular conductive elements. The effective magnetic flux through the Hall-effect sensor is dependent on the angle of rotation φ . The angular range that can be sensed is 180° here.

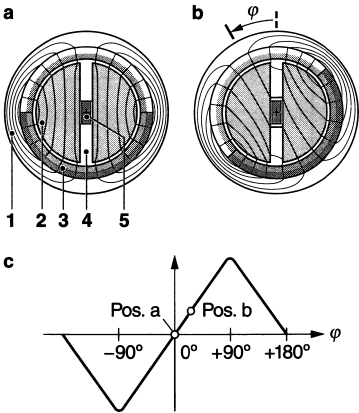
The Hall angular-position sensor with a measuring range of approximately 90° pictured in Figure 13a is derived from the basic "movable magnet" principle. The magnetic flux from a practically semicircular permanent-magnet disc is returned to the magnet through a pole-shoe, two additional conductive elements each of which contains a Hall sensor in its magnetic path, and the shaft which is also ferromagnetic. Depending upon the angular setting, the flux is led to a greater or

lesser degree through the two conductive elements, in the magnetic path of which a Hall sensor is situated. Using this principle, it is possible to achieve a practically linear characteristic curve (Figure 13b).

The simplified version pictured in Figure 14 does without soft magnetic conductive elements. In this version, the magnet moves around the Hall sensor in a circular arc (Figure 14a). Only a relatively small section of the resulting sinusoidal characteristic curve features good linearity. If the Hall sensor is located slightly outside the center of the circular arc, the characteristic curve increasingly deviates from the sinusoidal, and now features a short measuring range of almost 90° , and a longer measuring range of something more than 180° with good linearity. A great disadvantage though is the low level of shielding against external fields, as well as the remaining dependence on the geometric tolerances of the

Figure 12: Angular-position sensor using the movable-magnet principle

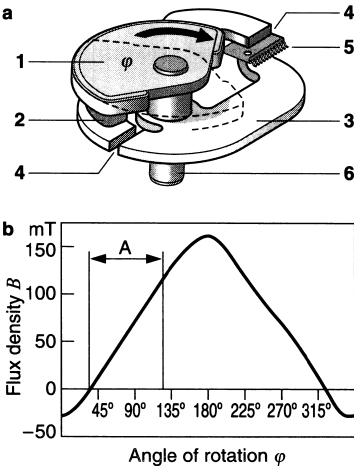
- a) Sensor in initial position,
 - b) Excursion through angle of rotation φ ,
 - c) Output signal.
- 1 Magnetic yoke,
 - 2 Stator (soft iron),
 - 3 Rotor (permanent magnet),
 - 4 Air gap,
 - 5 Hall sensor.
- φ Angle of rotation.



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Figure 13: Hall angular-position sensor with linear characteristic curve up to 90° using the movable-magnet principle

- a) Layout,
 - b) Characteristic curve with working range A.
- 1 Rotor disk (permanent magnet),
 - 2 Pole shoe,
 - 3 Conductive element,
 - 4 Air gap,
 - 5 Hall sensor, 6 Shaft.
- φ Angle of rotation.



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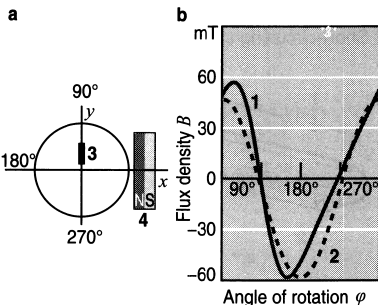
magnetic circuit, and the intensity fluctuations of the magnetic flux in the permanent magnet as a function of temperature and age.

In the Hall angular-position sensor pictured in Figure 15 it is not the field strength but rather the magnetic-field direction that is evaluated. The magnetic-field lines are sensed by four Hall elements lying in one plane and radially arranged in the x - and y -directions. The sensor is located between two magnets to generate a homogeneous magnetic field. The sensor signal is formed from the measurement signals of the Hall elements (sine and cosine signals) in an evaluation circuit using the arctan function.

Like the potentiometric accelerator-pedal sensor these systems also contain two measuring elements in order to obtain two redundant voltage signals for diagnostic purposes.

Figure 14: Hall angular-position sensor with linear characteristic curve up to 180° using the movable-magnet principle

- Principle (Hall IC in this depiction shifted from center point),
 - Characteristic curve.
- Curve for arrangement with Hall IC at center point,
 - Curve for arrangement with Hall IC outside center point,
 - Hall IC,
 - Magnet.



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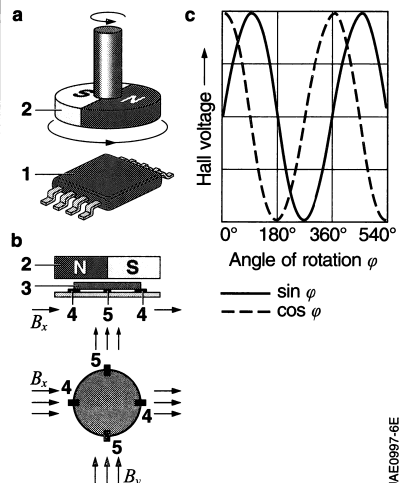
Magnetoresistive sensors

In contrast to the Hall sensors, the optimum chip shape for a magnetoresistor tends to be shorter and squatter, and represents a very low resistance. In order to arrive at technically applicable resistance values in the $k\Omega$ range, it is therefore necessary to connect a large number of these chips in series. This problem is solved elegantly by adding microscopically fine, highly conductive nickel-antimonide needles to the semiconductor crystal. These are located obliquely to the direction of current flow. A further measure is to apply meander techniques to the semiconductor resistor.

The dependence of the resistance on the magnetic flux density B follows a square-law function up to inductances of approximately 0.3 T, and above this point

Figure 15: Hall angular-position sensor with fourfold Hall sensor with evaluation of magnetic-field direction for a measurement range over 360°

- Layout,
 - Measurement principle,
 - Measurement signals.
- IC with Hall elements,
 - Magnet (the opposite magnet is not visible here),
 - Conductive element,
 - Hall elements for sensing the x component of B ,
 - Hall elements for sensing the y component of B .



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it is increasingly linear. There is no upper limit to the control range, and dynamic response in technical applications can – as is the case with the Hall sensor – be regarded as free from lag.

Since the temperature sensitivity has a pronounced effect on the resistance of magneto-resistors (approximately 50% reduction for 100 K), they are usually delivered only in the dual-configuration form in voltage-divider circuits (differential magneto-resistors). For the particular application, each of the two resistor sections must then be magnetically triggered (as far as possible with opposite polarities). Notwithstanding the high temperature coefficient of the individual resistors, the voltage-divider circuit guarantees good stability of the working-point (that point at which both resistor sections have the same value).

In order to achieve good measurement sensitivity, it is best to operate the magneto-resistors at a magnetic working point between 0.1 and 0.3 T. Generally, the required magnetic bias is supplied by a small permanent magnet (Figure 16) the effects of which can be increased by using a small magnetic return plate. The magneto-resistor features pronounced temperature sensitivity so that it is used almost exclusively in incremental angle-of-rotation and displacement sensors, or in binary limit-value sensors (with switch-

ing characteristic). A magnetoresistive increment sensor is used to measure start-of-injection adjustment in diesel distributor injection pumps.

The magnetoresistor's main advantage is its high signal level which is usually in the volts range. This means that amplification is unnecessary, as well as the local electronic circuitry and the associated protective measures which would otherwise be needed. Furthermore, in their role as passive, resistive components, they are highly insensitive to electromagnetic interference and, as a result of their high bias voltage, practically immune against external magnetic fields.

AMR sensors

Anisotropic magnetoresistive effect

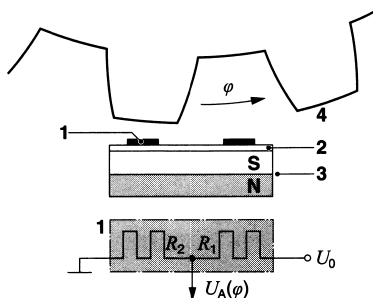
NiFe layers only roughly 30 to 50 nm thick display electromagnetically anisotropic properties, i.e. their electrical resistance changes under the influence of a magnetic field. Resistance structures of this type are therefore called AMR sensors (anisotropic magnetoresistive sensors). The metal alloy generally used is also called permalloy.

Types

On an elongated resistance strip, as shown in Figure 17a, a small, spontaneous magnetization M_s occurs in the longi-

Figure 16: Differential magnetoresistive sensor

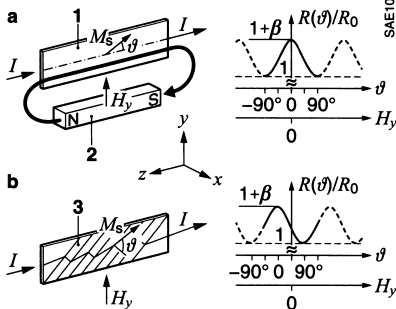
- 1 Magneto-resistors R_1 and R_2 ,
 - 2 Soft-magnetic substrate,
 - 3 Permanent magnet, 4 Gear.
- U_0 Supply voltage,
 $U_A(\varphi)$ Measurement voltage for angle of rotation φ .



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Figure 17: AMR basic principle

- a) Basic type,
 - b) Barber-pole type.
- 1 Magneto-resistive element (NiFe, NiCo),
 - 2 Bias magnet,
 - 3 Short-circuiting strip.



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tudinal direction of the conductor track even without the application of an external control field (form anisotropy). In order to give this magnetization a clearly defined direction – theoretically, it could be in the other direction – AMR sensors are often, as depicted, provided with weak bias magnets. In this state, the series resistance has its greatest value $R_{||}$. If the magnetization vector is rotated under the influence of an additional external field H_y through the angle ϑ , the series resistance decreases gradually until it assumes at $\vartheta = 90^\circ$ a minimum value $R_{\perp}$. Here, the resistance is only dependent on the angle ϑ contained by the resulting magnetization M_S and the current I ; it has a roughly cosinusoidal characteristic as a function of ϑ :

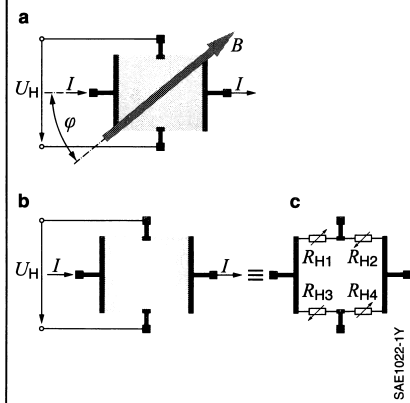
$$R = R_0(1 + \beta \cos^2 \vartheta).$$

Thus the following relationships are obtained for the maximum and minimum values:

$$R_{||} = R_0(1 + \beta) \text{ and } R_{\perp} = R_0.$$

Figure 18: Pseudo-Hall sensor

- a) Full basic form,
 - b) Modified form with hollowed-out surface,
 - c) Replacement circuit diagram for b).
- B Magnetic flux density,
 U_H Hall voltage,
 I Supply current,
 φ Angle of rotation,
 R_H Resistors of AMR elements.



The coefficient β denotes the maximum possible resistance variation, and is approximately 3%. If the external field is much stronger than the spontaneous magnetization, and this is usually the case when control magnets are used, the effective angle is almost completely a function of the direction of the external field. The field strength is now irrelevant, in other words, the sensor is now operating in the “saturated state”.

Highly conductive short-circuiting strips (for instance of gold) on the AMR film force the current to flow at an angle of below 45° to the spontaneous magnetization (longitudinal direction) without the application of an external field. In this version – also referred to as the “barber-pole” sensor – the sensor curve shifts by 45° compared to that of the simple resistor (Figure 17b). This means, therefore, that even when the external field strength $H_y = 0$, the curve is at the point of maximum measurement sensitivity (reversal point). The “striping of two resistors in opposite directions” means that they change their resistances in opposite directions under the effects of the same field. In other words, one of the resistances increases while the other drops.

In addition to the simple, two-pole AMR elements, there are also pseudo-Hall sensors, for instance square NiFe thin-film structures, which, like the normal Hall sensors already described, have four terminals: two for the current path and two transverse ones for picking off a Hall voltage (Figure 18a). Unlike a normal Hall sensor, however, a pseudo-Hall sensor is sensitive to magnetic fields in the film plane and not vertically to it. Also, a pseudo-Hall sensor does not demonstrate a proportional characteristic curve; instead, it has a sinusoidal curve with very high faithfulness of shape to the sine, which is in no way dependent on the strength of the control field and the temperature. For a field parallel to the current path, the output voltage disappears in order then to describe a sinusoidal half-period when the field is rotated up to the angle $\varphi = 90^\circ$. The sinusoidal voltage therefore results with amplitude $\hat{u}_H$ as follows:

$$U_H = \hat{u}_H \sin 2\varphi.$$

If the external control field is rotated once through $\varphi = 360^\circ$, the output voltage therefore follows two full sinusoidal periods. The amplitude $\hat{u}_H$ is, however, very much dependent on the temperature and the air gap between the sensor and the control magnet; it decreases as the temperature and the air gap increase.

The measurement sensitivity of this so-called pseudo-Hall element can be considerably increased (without excessively falsifying the sinusoidal shape) by "hollowing out" the element from the inside so that only the "frame" remains (Figure 18b). This modification converts the pseudo-Hall sensor to a full bridge consisting of four AMR resistors (Figure 18c). Even when the bridge resistors are meander-shaped, provided a given minimum conductor width is not dropped below, this still has negligible effect on the signal's sinusoidal shape.

Applications

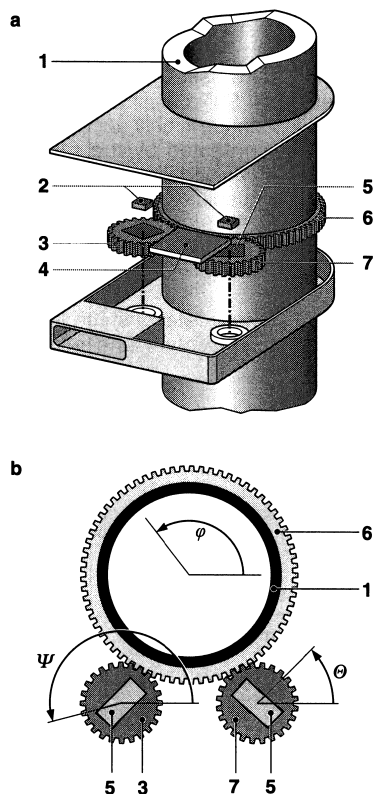
Steering-angle sensor

The function of driving-dynamics systems is to keep the vehicle on the desired course specified by the driver with targeted brake interventions. The steering-wheel angle must be known for this purpose. Potentiometers, optical code sensing and magnetic measurement principles are used for measurement.

A steering-wheel-angle sensor mounted on the steering shaft senses the steering-wheel position. Several rotations of the steering shaft can be measured with a dual configuration of pseudo-Hall angle-of-rotation sensors (each for 180°). The two associated permanent magnets are rotated via a high-ratio gear train (Figure 19). Because the two smaller output gears, which carry the control magnets, differ by one tooth, their mutual phase angle (difference of angles of rotation: $\Psi - \Theta$) is a clear measure of the absolute angular position of the steering shaft. The system is designed in such a way that this phase difference does not exceed 360° for a total of four rotations of the steering shaft, and thereby the clearness of the measure-

Figure 19: AMR steering-angle sensor

- a) Layout,
- b) Angle relations.
- 1 Steering shaft,
- 2 AMR measuring cells,
- 3 Gear with m teeth,
- 4 Evaluation electronics,
- 5 Magnets,
- 6 Gear with $n > m$ teeth,
- 7 Gear with $m + 1$ teeth.



ment is assured. Each individual sensor also offers an indeterminate fine resolution of the angle of rotation. It is possible with such an arrangement to resolve the full steering-angle range, for example, more accurately than 1° .

GMR sensors

Giant magnetoresistive effect

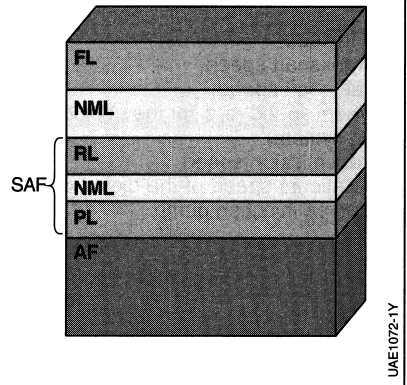
GMR-sensor technology (giant magnetoresistive sensor) is used in automotive applications for angular-position and rpm sensing. The main advantages of GMR sensors over AMR sensors are the natural clearness range within 360° for angular-position sensing and the higher magnetic-field sensitivity for rpm sensing.

GMR layer structures consist of anti-ferromagnetic, ferromagnetic and non-magnetic function layers (Figure 20). The individual layer thicknesses in both systems are in the range of 1 to 5 nm, and therefore only comprise a few atom layers. For angular-position sensing the required reference magnetization is generated by the fact that the direction of magnetization of one of the ferromagnetic layers (PL) is pinned by the interaction with a neighboring antiferromagnetic layer (AF). This is therefore also referred to as a “pinned layer”. On the other hand, the magnetization of the second ferromagnetic layer (FL) magnetically isolated to a large extent via a non-magnetic interlayer (NML) can be freely rotated with the external magnetic field. This is accordingly referred to as a “free layer”.

The resistance changes with a cosinusoidal dependence on the angle between the external field direction and the reference direction. Crucial to the accuracy of the angular-position measurement is the stability of the reference magnetization against the effect of the external field. This stability is greatly increased by using an additional artificial antiferromagnet (SAF).

Figure 20: GMR layer structure

FL Free layer,
NML Non-magnetic interlayer,
RL Reference layer,
PL Pinned layer,
AF Antiferromagnet,
SAF Artificial antiferromagnet.



Applications of GMR sensors

Steering-wheel-angle sensor

The mechanical structure and the operating principle of this GMR sensor is equivalent to those of the steering-wheel-angle sensor with AMR elements. In view of the greater sensitivity in comparison with the AMR effect the GMR sensor can operate with weaker magnets and larger air gaps. This results in costs benefits with regard to materials and design. The 360° angular-position measurement range of a single GMR element (180° is typical for AMR) enables smaller gears to be used. This in turn means that it takes up less space.

References for position sensors

- [1] K. Reif (Editor): *Klassische Diesel-Einspritzsysteme – Bosch Fachinformation Automobil*. 1st Ed., Vieweg+Teubner, 2012.
- [2] K. Reif (Editor): *Sensoren im Kraftfahrzeug – Bosch Fachinformation Automobil*. 3rd Ed., Verlag Springer Vieweg, 2016.

Rpm sensors

Measured variables

rpm sensors measure the time required for an angle to be covered during a rotational motion. From this the number of revolutions per unit of time can be determined. In a motor vehicle this usually involves relative measured variables which occur between two components. Examples include:

- Crankshaft speed,
- Camshaft speed,
- Wheel speed (e.g. for the antilock braking system),
- Transmission speed,
- Rotational speed of the diesel distributor-type injection pump.

Measurement principles

rpm sensing usually occurs with an incremental sensor system, consisting of a rotor (e.g. gear or multipole wheel) and the rpm sensor (Figure 1).

Passive rpm sensors

Conventional inductive sensors used in the past were based on the inductive measuring effect. A sensor of this type consists of a permanent magnet and a soft magnetic pole pin surrounded by an induction coil. The pole pin is opposite a ferromagnetic gear. The distance between the gear and the pole pin changes as the gear turns. The time change in the magnetic flux that this causes gives rise to an induced voltage in the coil.

The measuring effect of the inductive sensor is relatively high, eliminating the need for local electronics. It is therefore called a passive sensor. However, the signal amplitude is rotational-speed-dependent. The sensor is therefore unsuitable for the lowest rotational speeds; it permits only a comparatively small air-gap tolerance between pole pin and gear and for the most part is not able to distinguish air-gap fluctuations (chatter) from rotational-speed pulses.

Passive rpm sensors are still used today in commercial vehicles.

Active rpm sensors

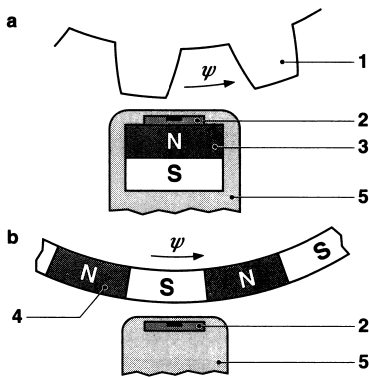
Active rpm sensors operate in accordance with the magnetostatic principle. The amplitude of the output signal is not dependent on the rotational speed. rpm sensing is thus possible even at very low rotational speeds (quasistatic rpm sensing).

Hall sensor

A voltage U_H proportional to the magnetic field (Hall voltage) can be picked off transversely to the current direction on a current-carrying wafer which is permeated vertically by a magnetic induction B (see Hall effect). In the sensor arrangement with a ferromagnetic gear (pulse wheel) the magnetic field is generated by a permanent magnet (Figure 1a). Located between the magnet and the pulse wheel is the Hall-sensor element. The magnetic flux which permeates this element depends on whether the sensor is opposite a tooth or a gap. This results in a Hall voltage that is equivalent to the progression of the teeth. This rotational-speed infor-

Figure 1: Hall sensors

- a) Sensor arrangement with passive rotor (ferromagnetic gear),
- b) Sensor arrangement with active rotor (multipole wheel).
- 1 Increment rotor,
- 2 Hall IC,
- 3 Permanent magnet,
- 4 Multipole wheel,
- 5 Housing.



mation is conditioned and amplified, and then transmitted as injected current in the form of square-wave signals. Typical values are 7 mA for the low level and 14 mA for the high level. The current is converted into a signal voltage by a measuring shunt in the ECU.

In a differential Hall sensor there are two Hall-sensor elements situated between the magnet and the pulse wheel. Determining the difference between the signals from the two sensor elements reduces magnetic interference signals and improves the signal-to-noise ratio.

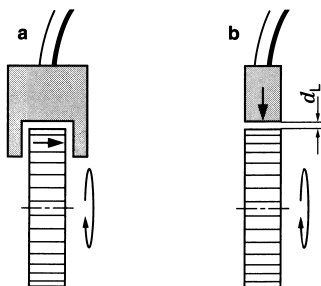
Multipole wheels are also used instead of the ferromagnetic pulse wheel. Here, a magnetizable plastic is applied to a non-magnetically metallic substrate and alternately magnetized. These north and south poles assume the function of the teeth of a pulse wheel (Figure 1b).

AMR sensor

The electrical resistance of magnetoresistive material (AMR, Anisotropic Magneto Resistive) is anisotropic, i.e. it is dependent on the direction of the magnetic field to which it is exposed. This property is exploited in the AMR sensor. The sensor is located between a magnet and the pulse wheel. The magnetic field lines change their direction when the pulse wheel turns. This gives rise to a sinusoidal voltage which is amplified in an evaluation circuit in the sensor and converted into a square-wave signal.

Figure 2: Different sensor shapes

- a) Fork shape (vane principle),
b) Rod shape (proximity principle).
 d_L Air gap.



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GMR sensor

The use of GMR technology (Giant Magneto Resistance) constitutes a further development of active sensors. Their greater sensitivity than AMR sensors means that larger air gaps are possible, which in turn opens up the possibility of use in difficult areas of application. The greater sensitivity also means lower noise at the signal edges.

Sensor shapes

Different sensor shapes are used (Figure 2): the rod shape, the fork shape, and the inner and outer ring shape. Due to its ease of mounting and simplicity, the rod sensor is the most widespread sensor shape. The rod sensor is located near the rotor, the teeth of which approach it and pass by in close proximity. However, it also has the lowest measurement sensitivity. The fork-shaped sensor, which is insensitive to axial and radial play, is permissible in some cases, and is also in service in the field. This sensor must be roughly aligned to the rotor when installed. The sensor type in which the sensor surrounds the rotor shaft in the form of a ring is practically no longer used.

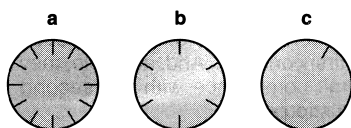
Rotor shapes

In the incremental detection of relative yaw rate, depending upon the number and size of the scanned peripheral rotor markings, a distinction is made between the following types of sensor (Figure 3):

- Simple sensor, with only a single scanned marking per revolution, so that only the average rotational speed can be registered,

Figure 3: Recording of relative rotational speed

- a) Increment sensor,
b) Segment sensor,
c) Simple rpm sensor.



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- Segment sensor, with only a small number of scanned peripheral segments (for instance, equivalent to the number of engine cylinders),
- Increment sensor with closely spaced peripheral markings. Up to a certain point, this form of sensor permits instantaneous speed to be measured at points on the circumference, and thus the registration of very fine angular divisions.

The rotor is crucially important to measuring rotational speed; however, it is usually part of the vehicle manufacturer's delivery specification, while the actual sensor comes from the supplier. The rotors used almost exclusively up to now have been magnetically passive types, which therefore consist of soft-magnetic material, usually iron. They are cheaper than hard magnetic pole wheels and are easier to handle, since they are not magnetized, and there is no danger of mutual demagnetization during storage. As a rule, presuming the same increment width and output signal, the pole wheel's intrinsic magnetism (a pole wheel is defined as a magnetically active rotor) permits a considerably larger air gap.

Demands made of rpm sensors

The following demands are made of rpm sensors:

- Static detection (i.e. speed approaching zero, extremely low engine-starting and wheel speeds),
- Large air gaps (non-adjusted mounting on air gap greater than zero),
- Small size,
- Efficient operation independent of air-gap fluctuations,
- Heat-resistant up to 200 °C,
- Identification of the direction of rotation (optional for navigation),
- Reference-mark identification (ignition).

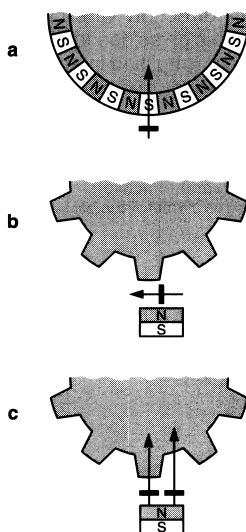
Magnetostatic sensors (e.g. Hall sensors, AMR sensors) are suitable for satisfying the first condition. And, as a rule, they also permit compliance with the second and third stipulations.

Figure 4 shows three basically suitable sensor shapes which generally are insensitive to air-gap fluctuations. Here, a dis-

inction must be made between sensors which sense radially and those which sense tangentially (see also Figure 5). This means that independent of the air gap, magnetostatic sensors are always able to differentiate between the north and south poles of a magnetically active pole wheel. In the case of magnetically passive rotors, the sign of the output signal is then no longer independent of the air gap when they register the tangential-field strength (here though, the fact that the air gap is often enlarged due to the rotor is a disadvantage). Here, though, the fact that the air gap between the rotor and the permanent magnet is often enlarged due to the sensor is a disadvantage. However, types frequently used as well are radially measuring differential-field or gradient sensors, which essentially only register the gradient of the radial field component,

Figure 4: Sensor arrangements which are insensitive to air-gap fluctuations

- a) Radial-field sensor with pole wheel,
 b) Tangential sensor,
 c) Differential sensor with gear.
 The sensor measures that part of the magnetic field in a certain direction in space. The arrow marks this direction.



which changes with regard to its sign not with the air gap, but only with the angle of rotation.

In the case of wheel-speed sensors, at the least the sensor tip, because of its proximity to the brake, should be able to withstand higher temperatures.

Sensor arrangements

Gradient sensors

Gradient sensors (e.g. based on differential Hall sensors) incorporate a permanent magnet on which the pole surface facing the gear is homogenized with a thin ferromagnetic wafer. Two sensor elements are located on each element's sensor tip, at a distance of roughly one half a tooth interval. Thus, one of the elements is always opposite a gap between teeth when the other is opposite to a tooth. The sensor measures the difference in field intensity at two adjacent locations on the circumference. The output signal is roughly proportional to the diversion of field strength as a function of the angle at the circumference; polarity is therefore independent of the air gap.

Tangential sensors

Tangential sensors differ from gradient sensors by their reaction to variations in polarity and intensity in the components of a magnetic field located tangentially to

the periphery of the rotor. Design options include AMR thin-film technology (barber pole) or single permalloy resistors featuring full- or half-bridge circuits [1]. In contrast to gradient sensors, they need not be matched to the particular tooth pitch of the rotor and can be designed to sense at a given point. Local amplification is necessary, even though their measuring effect is 1 to 2 orders of magnitude larger than that of the silicon-Hall sensors.

In the case of a bearing-integrated crankshaft speed sensor (Simmer shaft-seal module), the AMR thin-film sensor is mounted together with an evaluation IC on a common lead frame. For the purposes of space saving and temperature protection, the evaluation IC is bent at an angle of 90° and also located further away from the sensor tip.

Applications

Crankshaft-speed sensor

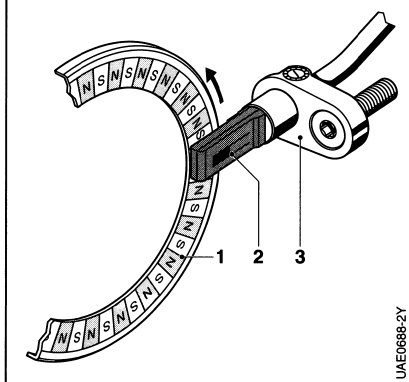
Crankshaft-speed sensors are used to measure the engine speed (crankshaft speed). In addition, the engine-management system requires the position of the crankshaft (position of the pistons) to be able for example to activate ignition coils and fuel injectors at the correct crank angle. The pulse wheel mounted on the crankshaft exhibits a tooth gap for this purpose. With a tooth pitch of 6° and two missing teeth the pulse wheel has 58 teeth. The rpm sensor delivers a square-wave signal (tooth signal) that corresponds to the teeth on the pulse wheel.

The microcontroller in the engine ECU records the value of a running timer at the falling edges of the signal and forms the tooth spacing in terms of time from the difference between two edges. At the first tooth after the gap the measured time is very much greater than the preceding time; at the second tooth after the gap the time is again very much less. This tooth is defined as the reference mark. The pulse wheel is mounted so that this position corresponds to a defined angle opposite the top dead center of cylinder no. 1.

At uniform rotational speed the time between the edges around the tooth gap is three times as long as between two normal edges. Even in the event of greatly fluctuating rotational speed when

Figure 5: AMR rpm sensor as tangential-field sensor

- 1 Multipole ring,
- 2 Measuring cell,
- 3 Sensor housing.



the engine is being started, the reference mark can be reliably inferred on account of the measured differences of the tooth spacing.

Camshaft-speed sensor

The camshaft is stepped down by a ratio of 1:2 compared with the crankshaft. It indicates whether a piston moving to top dead center is in the compression cycle or the exhaust cycle. For this reason a camshaft-speed sensor is required in addition to the crankshaft-speed sensor.

Simple pulse wheels lead to different sensor-signal levels only in the area of the reference mark. More complex pulse wheels with segments of different lengths enable the engine position to be detected more quickly when starting and thus provides for rapid starting.

Wheel-speed sensor

Wheel-speed sensors sense the rotational speed of the wheels. This information is needed for example by the driving-dynamics control to calculate the driving speed and the slip. The navigation system requires the wheel-speed signals to calculate the distance traveled when there is no GPS reception (e.g., in tunnels).

The pulse wheel is permanently connected to the wheel hub. Both steel pulse wheels and multipole rings can be used. This sensor has fewer teeth because the pulse wheel is smaller in diameter than that on an engine rpm sensor.

The sensor element with the signal amplifier and signal conditioning is integrated in an IC, hermetically sealed with plastic, and seated in the sensor head.

Digital signal conditioning enables encoded additional information to be transmitted via a pulse-width-modulated output signal. One example is direction-of-rotation detection, which is required for Hill Hold Control that prevents the vehicle from rolling back when starting. The direction of rotation is also used for vehicle navigation to detect backing up (reversing).

Speed sensor for transmission control

Transmission-speed sensors sense shaft speeds in automatic transmissions. Standard geometries are generally not possible due to the compact designs of transmissions. Specific sensor versions are therefore required for each transmission. Evaluation circuits with varying degrees of evaluation-algorithm complexity are used to cover the full spectrum of functional requirements.

References for rpm sensors

[1] K. Reif (Editor): Sensoren im Kraftfahrzeug. 2nd Ed., Springer-Vieweg, 2012.

Oscillation gyrometers

Measured variables

Oscillation gyrometers measure the absolute yaw rate along the vehicle vertical axis, the vehicle transverse axis (pitch axis), and the vehicle longitudinal axis (roll rate). The signals generated here are used in numerous systems such as for example driving-dynamics control, rollover protection systems, vehicle navigation, and damping control.

Measurement principle

Oscillation gyrometers are similar in principle to mechanical gyroscopes and for measurement purposes utilize the Coriolis acceleration a_c that occurs during rotary motion in conjunction with an impressed oscillating motion (Figure 1). The acceleration is calculated from the cross product of velocity and yaw rate:

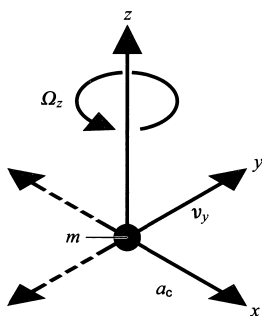
$$(1) \vec{a}_c = \vec{a}_x = 2 \vec{v}_y \times \vec{\Omega}_z.$$

The velocity v is produced by the sinusoidal driving of the inert mass of the sensor along its y -axis at frequency ω . Thus:

$$(2) v_y = \hat{v}_y \sin(\omega t).$$

Figure 1: Creation of Coriolis acceleration

When a mass point m moves in the y -direction at velocity v_y and the system simultaneously rotates about the vertical axis z with yaw rate Ω_z , the mass point experiences a Coriolis acceleration a_c in the x -direction.



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With a constant yaw rate Ω about the z -axis a Coriolis acceleration is produced along the x -axis. It has the same frequency and phase as the drive velocity v , and the associated amplitude is

$$(3) \hat{a}_c = 2 \hat{v}_y \Omega_z.$$

The Coriolis force is one of the so-called pseudo forces and can only be measured in the rotating reference system (like the passenger car here).

The signal evaluation of the sensor demodulates the sinusoidal Coriolis signal of the micromechanical sensor ($a_c \propto \sin(\omega t)$) and in this way determines the yaw rate Ω . In the process, unwanted acceleration from the outside (e.g. bodywork acceleration) is removed.

The utilized measuring effects not only are very small, but also require complex signal conditioning. Signal conditioning directly at the sensor is therefore necessary.

Applications

Micromechanical yaw-rate sensors

A seismic mass in the sensor must be induced to vibrate in order to generate a Coriolis force to measure a yaw rate. In a micromechanical yaw-rate sensor (Figure 2) this is achieved in a permanent-magnet field by utilizing the Lorentz force (electrodynamical drive).

This sensor is based on a formulation of bulk micromechanics: Two thick oscillating elements fashioned from the wafer by means of bulk micromechanics oscillate in push-pull mode at their resonant frequency (< 2 kHz), which is determined by their mass and their coupling-spring stiffness. Each of them is provided with a capacitive, surface-micromechanical acceleration sensor (SMM) which measures Coriolis acceleration.

For drive purposes a sinusoidally modulated current is passed through a simple printed conductor on the relevant oscillating element. This generates within the permanent-magnetic field operating perpendicularly to the chip surface a Lorentz force which starts the oscillating element moving.

If this sensor is rotated at yaw rate Ω about the vertical axis, the drive in the oscillation direction results in a Coriolis acceleration which is measured by the acceleration sensors.

The different physical natures of the drive and sensor systems prevent unwanted crosstalk between the two parts. In order to suppress external acceleration (common-mode signal), the two opposing sensor signals are subtracted from each other. Summation, however, can also be used to measure the external acceleration).

The high-precision micromechanical construction helps to suppress the effects of high oscillatory acceleration which is several factors of 10 higher than the low-level Coriolis acceleration (cross sensitivity far below 40 dB). The drive and measuring systems are mechanically and electrically isolated in rigorous terms here.

Surface-micromechanical yaw-rate sensors

Micromechanical yaw-rate sensors can also be manufactured entirely using SMM technology (surface micromechanics). Here the oscillating element is electrostatically driven by capacitors. In this case the isolation of the drive and detection systems is not longer strictly separated from each other since both systems are capacitive in design.

A centrally mounted rotary oscillator is electrostatically driven to oscillate using comb structures (Figure 3). When the sensor is subjected to a rotation Ω , the Coriolis force induces a simultaneous "out-of-plane" tilting motion. Its amplitude is proportional to the yaw rate and is detected capacitively by electrodes located under the rotary oscillator. To prevent this motion from being excessively damped, it is essential to operate the sensor in a vacuum.

The smaller chip size and the simpler manufacturing process do indeed reduce the cost of such a sensor, but the reduction in size also diminishes the already slight measuring effect and thus the attainable accuracy. It places higher demands on the electronics.

Figure 2: Micromechanical yaw-rate sensor with electrodynamic drive

- 1 Oscillation direction,
 - 2 Oscillating element,
 - 3 Coriolis acceleration sensor,
 - 4 Retaining and guide spring,
 - 5 Direction of Coriolis acceleration,
- Ω Yaw rate,
 v Oscillation velocity,
 B Magnetic flux density.

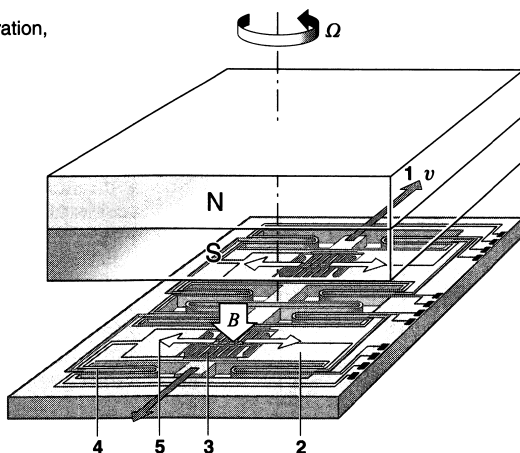


Figure 3: Surface-micromechanical yaw-rate sensor with electrostatic drive

1 Comb structure, 2 Rotary oscillator, 3 Measurement axis.

C_{Drv} Capacitance of drive electrodes (drive by application of a sinusoidal voltage),

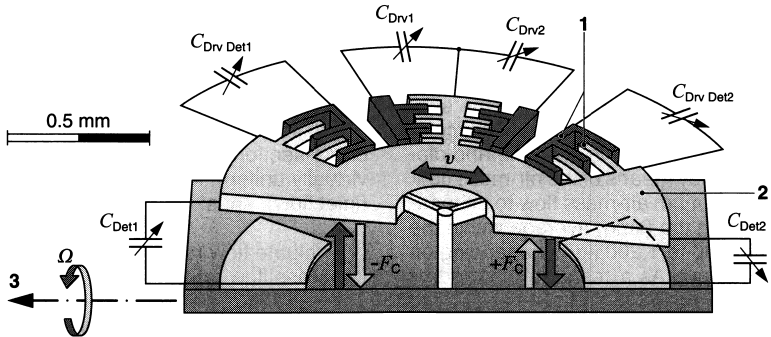
C_{Det} Capacitance of rotary-oscillation tap (measurement of Coriolis force),

C_{DrvDet} Capacitance of drive tap (measurement of drive oscillation),

F_C Coriolis force,

v Oscillation velocity,

Ω Yaw rate to be measured ($\Omega = \text{const} \cdot \Delta C_{Det}$).



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The influence of external accelerations is suppressed in SMM yaw-rate sensors by a special micromechanical design. Here the MEMS element (MEMS, Micro-Electro-Mechanical Systems) exhibits two seismic masses. Their deflection is effected by Coriolis forces in opposite directions, but by external accelerations in the same direction. A differential evaluation of the two oscillators then frees the signal of the unwanted disturbance values.

Further developments of yaw-rate sensors

Ongoing development of systems in the field of active and passive safety means that increased demands are placed on the signal quality and robustness of the yaw-rate sensor. These systems require not only the measurement of the yaw rate, but also the detection of pitching and rolling motion.

For example, a driving-dynamics control system is based among other things on measurement of the yaw rate Ω_z and on measurement of the lateral acceleration a_y . ACC systems (Adaptive Cruise Control) utilize sensor signals of the yaw rate Ω_z , the lateral acceleration a_y , and the linear acceleration a_x . Rollover protection systems on the other hand use sensor information about the roll axis Ω_x , the vertical acceleration a_z , and also the lateral acceleration a_y .

New sensor generations of micromechanical sensor elements are used here. These sensors measure the yaw rate about either the x -axis or the z -axis; many of these sensors also incorporate sensing elements for detecting accelerations in the x -, y - or z -direction.

Measurement of the yaw rate is based here on the principle of the surface-micromechanical yaw-rate sensor, while accelerations are detected with capacitive surface-micromechanical acceleration sensors.

Flowmeters

Measured variables

The amount of air supplied to the engine must be measured in order to control the combustion process. The mass ratios are the main factors in the chemical process of combustion, thus the actual objective is to measure the mass flow of the intake and charge air. The air-mass flow is the most important load variable in gasoline engines; precise pilot control of the air/fuel ratio presupposes knowledge of the supplied air mass. The exhaust-gas recirculation rate is regulated in gasoline and diesel engines by means of the air-mass flow.

The maximum air-mass flow to be measured lies in the (time) average within the range of 400 to 1,200 kg/h, depending on engine output. As a result of the modest idle requirements of modern engines, the ratio between minimum and maximum air flow is 1:90 to 1:100 in gasoline engines and due to the higher idle requirements 1:20 to 1:40 in diesel engines. Because of stringent exhaust-emission and consumption requirements, levels of accuracy of 1 to 2% from the measured value must be achieved. Referred to the measurement range, this can mean an – unusually high for motor vehicles – measurement accuracy of 10^{-4} .

The air is not drawn in continuously by the engine, but rather in time with the opening of the intake valves. For this reason, the air flow pulses strongly – particularly with the throttle valve wide open – at the measuring point (Figure 1). The measuring point is always located in the intake

tract between the air filter and the throttle valve. Due to resonances of the intake manifold, pulsation of the intake manifold – above all in 4-cylinder engines in which the induction or charge phases do not overlap – is so strong that even brief reverse flows occur. These must be correctly detected by an accurate flowmeter.

Applications and measurement principles

Pitot-tube flowmeters

A medium of uniform density at all points flows through a tube with a constant cross-section A at a velocity v which is virtually uniform in the tube cross-section (inlet flow). Thus:

- (1) Volume flow rate $Q_V = v A$,
- (2) Mass flow rate $Q_M = \rho v A$.

If an orifice plate is then installed in the flow duct, forming a restriction, this will result in a pressure differential (dynamic pressure) Δp in accordance with Bernoulli's Law. Thus:

$$(3) \Delta p = \text{const} \cdot \rho v^2 = \text{const} \cdot Q_V Q_M,$$

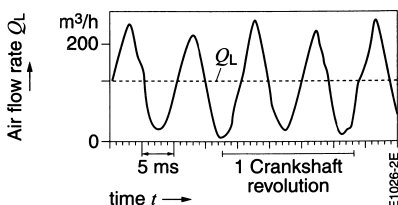
where the constant is dependent on the tube and the orifice-plate cross-sections. This pressure difference can be measured directly with a differential-pressure sensor or as a force acting on a sensor plate. Pivoting, variable-position sensor flaps (Figure 2) leave a variable section of the flow cross-section unobstructed, with the size of the free diameter being dependent on the flow rate. The sensor plate is pressed as the flow increases against a mostly constant counterforce. A potentiometer monitors the characteristic flap positions for the respective flow rates.

Measurement errors can occur in cases where the sensor-plate mechanical inertia prevents it from keeping pace with a rapidly pulsating air current (full-load condition at high engine speeds).

If the density ρ changes due to temperature fluctuations or the altitude, the measurement signal changes with $\sqrt{\rho}$. An air-temperature sensor and a barometric pressure sensor must be used to compensate for this.

Figure 1: Qualitative characteristic of intake-air pulsation in a 4-cylinder gasoline engine

Operating point: $n = 3,000$ rpm, full load.
 Q_L Mean air flow rate.



The higher sensitivity of the output signal required for a large measurement range with small air masses is obtained from the mechanical and electrical design of the air-flow sensor used in for example the earlier L-Jetronic gasoline injection system. Air-flow sensors for KE-Jetronic are designed for a linear characteristic.

This method of flow measurement has not been used in new developments for some time now.

Hot-wire air-mass meters

Hot-wire air-mass meters operate without mechanically moving parts. The hot wire is made from for example platinum whose electrical resistance R increases with temperature. The wire heats up when a current I_H is passed through it. It is cooled when it is in an air flow. The cooling process reduces the resistance of the wire and increases the electric current to produce an equilibrium between the input power P_{el} and the power P_V output by the flow:

$$(4) P_{el} = I_H^2 R = P_V = c_1 \lambda \Delta T.$$

The dimensions of the hot wire and its air flow assume the constant c_1 . The heat conduction λ is approximately proportional to the root of the mass flow ($\sqrt{Q_M}$). Furthermore, if thermal convection is taken into consideration with the medium at rest (no air flow) with the coefficient c_2 ,

the following equation is obtained for the heating current I_H :

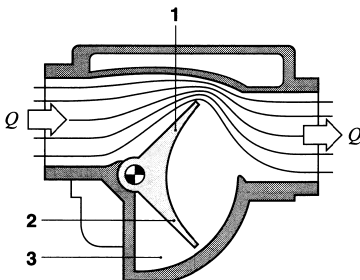
$$(5) I_H = c_1 \cdot \sqrt{(\sqrt{Q_M} + c_2)} \cdot \sqrt{\frac{\Delta T}{R}}.$$

The closed-loop control circuit in the sensor housing (Figure 3, the controller is shown as a box) maintains the heater element (platinum hot wire) at a constant overtemperature in relation to the air temperature. The air temperature is taken into consideration with the compensation resistor R_K , whose resistance value is dependent on the air temperature. The current required for heating provides an extremely precise – albeit nonlinear – index of air-mass flow rate. The associated ECU generally converts the signal into linear form and performs other signal-evaluation tasks, with the air-mass meter signal being sensed in millisecond intervals. Due to its closed-loop design, this type of flowmeter can also monitor fast flow-rate variations in the millisecond range since, because of the constant overtemperature of the heater element, its heat content does not have to be changed by means of time-consuming heat transfers.

However, the flow direction is not recognized with this method, and for this reason

Figure 2: Pitot-tube flowmeter

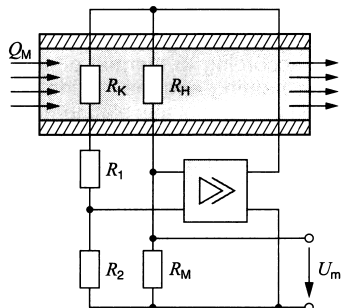
- 1 Sensor flap,
 - 2 Compensation flap,
 - 3 Damping volume.
- Q Flow.



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Figure 3: Electronic control of hot-wire air-mass meter

- Q_M Mass flow,
 U_m Measurement voltage,
 R_H Hot wire,
 R_K Compensation resistor,
 R_M Measuring resistor,
 R_1, R_2 Trimming resistor.



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these sensors sometimes exhibit substantial deviations when strong pulsations occur in the intake manifold.

To ensure stable and reliable performance throughout an extended service life, the system must burn off all accumulated deposits from the hot wire's surface at approx. 1,000 °C after each phase of active operation (when the ignition is switched off).

The hot-wire air-mass meter was used in earlier engine-management systems (Motronic) and has since been replaced by the hot-film air-mass meter (HFM).

Hot-film air-mass meters using thick-film technology

The first hot-film air-mass meter still manufactured using thick-film technology (HFM2 from Bosch) operates according to the same principle as the hot-wire air-mass meter, but combines all the measuring elements and the control electronics on a single substrate. The flat-design heating resistor is located on the back of the base wafer, with the corresponding temperature sensor on the front. The greater thermal inertia of the ceramic wafer results in somewhat greater response lag than that associated with the hot-wire air-mass meter. The compensation resistor and the heater element are thermally decoupled by means of a laser cut in the ceramic substrate. More favorable air-flow characteristics make it possible to dispense with the hot-wire meter's burn-off decontamination process.

Micromechanical hot-film air-mass meters

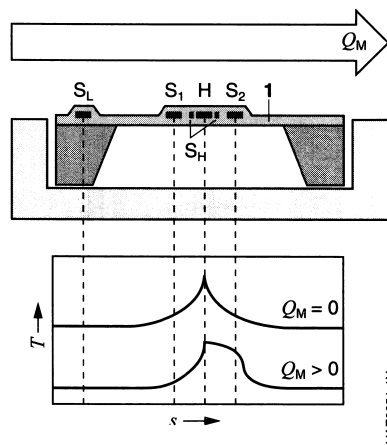
Extremely compact micromechanical hot-film air-mass meters (HFM5, HFM6, and HFM7 from Bosch, Figure 4) also operate according to thermal principles. Here the heating and measuring resistors are in the form of thin platinum layers sputtered (vapor-deposited) onto the silicon chip acting as substrate. Thermal decoupling from the mounting is obtained by installing this chip in the area of the heating resistor H on a micromechanically thinned section of the substrate (similar to a pressure-sensor diaphragm). The adjacent heater-temperature sensor S_H and the air-temperature sensor S_L (on

the thick edge of the silicon chip) maintain the heating resistor H at a constant overtemperature. This method differs from earlier techniques in dispensing with the heating current as an output signal. Instead, the signal is derived from the temperature difference in the diaphragm detected by the two temperature sensors S_1 and S_2 . Temperature sensors are located in the flow path upstream and downstream from the heating resistor H. Without air inflow the temperature profile is the same on both sides of the heating zone; for the temperature at the measuring points $T_1 = T_2$ applies (Figure 4).

If, on the other hand, air flows through the sensor measuring cell, the area upstream of the heater element is cooled by the cold air and a lower temperature is measured at S_1 . Downstream of the heater element the air flowing past is heated by the heater element; a higher temperature is therefore measured at S_2 .

Figure 4: Sensor element of micro-mechanical hot-film air-mass meter

- 1 Dielectric diaphragm,
- H Heating resistor,
- S_H Heater-temperature sensor,
- S_L Air-temperature sensor,
- S_1, S_2 Temperature sensors (upstream, downstream),
- Q_M Air-mass flow,
- s Measurement point,
- T Temperature.



The temperature difference is, irrespective of the absolute temperature of the air flowing past, a measure of the mass of the air flow. Although (as with the earlier process) the response pattern remains nonlinear, the fact that the initial value also indicates the flow direction represents an improvement over the former method using the heating current (Figure 6).

In the HFM5 the evaluation electronics integrated in the sensor convert the temperature difference measured at S_1 and S_2 with the aid of an analog circuit into an analog voltage signal between 0 V and 5 V. In the HFM6 and HFM7 the signal is processed with the aid of digital electronics to achieve greater accuracy and a frequency signal is generated. The HFM7 is a further-developed version of the HFM6 with improved electronics and the possibility of outputting an analog signal as an alternative to the frequency signal. This voltage or the frequency is converted in the engine ECU via the sen-

sor curve stored in the program into an air-mass flow.

The hot-film air-mass meter projects with its housing into a measuring tube (Figure 5). A flow rectifier mounted on the measuring tube (e.g. a wire grill) ensures a uniform flow in the measuring tube. The measuring tube is installed after the air filter in the intake tract.

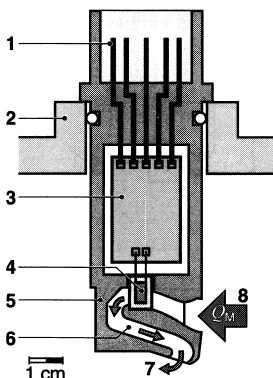
Because of the small size of the measuring element, this flowmeter is a partial flowmeter, which detects only a specific and very small part of the total flow. The constancy and reproducibility of this division factor have a direct impact on the accuracy of the sensor. A calibration establishes the interrelationship between the air mass Q_M flowing through the measuring tube and the measurement signal generated from the partial air flow.

The inlet and outlet to the micromechanical measuring element are designed and optimized in such a way that heavier particles, such as dust particles and liquid droplets, do not approach the measuring element directly, but are rather diverted ahead of it. As well as the changed form of signal processing the HFM6 and HFM7 feature a modified measuring passage in order to provide improved protection against contamination directly upstream of the sensor element.

The HFM7 is the current Bosch air-mass sensor that is used in engine-management systems for gasoline and diesel engines.

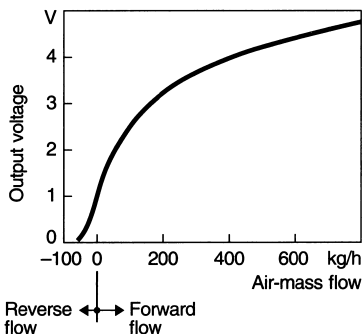
Figure 5: Section through hot-film air-mass meter

- 1 Electrical connections,
- 2 Measuring-tube or air-filter housing wall,
- 3 Evaluation electronics (hybrid circuit),
- 4 Sensor measuring cell,
- 5 Sensor housing,
- 6 Partial-flow measuring passage,
- 7 Outlet, partial air flow Q_M ,
- 8 Inlet, partial air flow Q_M .



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Figure 6: Characteristic curve of hot-film air-mass meter



UMK1691-2E

Acceleration and vibration sensors

Measured variables

The acceleration values a to be measured in motor vehicles are frequently expressed as a multiple of gravitational acceleration g ($1\text{ g} \approx 9.81\text{ m/s}^2$). Acceleration and vibration sensors are used in the following applications:

- Triggering restraint systems such as e.g. airbag and seat-belt pretensioner (35...100 g).
- Side-impact and upfront sensing (100...500 g).
- Rollover detection (3...7 g).
- Sensing acceleration by the vehicle for the antilock braking system (ABS) and driving-dynamics control (0.8...1.8 g).
- Evaluating bodywork acceleration for chassis control systems: body acceleration (1...2 g), axle and damper (10...20 g).
- Detecting changes in vehicle inclination for anti-theft alarm systems (approx. 1 g).
- Knock control in gasoline engines (measurement range up to 40 g).

Measurement principles

Acceleration sensors measure the force exerted by an acceleration a on an inert mass m :

(1) $F = ma$.

There are both position- and (mechanically) stress-measuring systems.

Position-measuring systems

Position-measuring systems are used particularly in the range of very small accelerations. All acceleration sensors are spring-bound right down to the gravitational pendulum. In other words, the inert mass is elastically connected to the body whose acceleration a is to be measured (Figure 1a).

Excursion-measuring sensor

In the static case the acceleration force is in equilibrium with the restoring force applied to the spring which has been deflected by x :

(2) $F = ma = cx$
where c = spring constant.

The resulting excursion is converted by means of a suitable measurement method (e.g. piezoelectric, capacitive, piezoresistive or thermal) into an electrical signal.

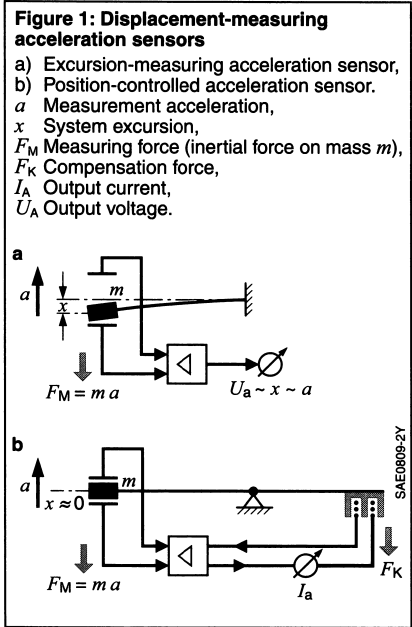
The system's measurement sensitivity S is therefore:

(3) $S = \frac{x}{a} = \frac{m}{c}$.

In other words, a large mass together with low spring stiffness (or constant) result in high measurement sensitivity.

In the dynamic case a damping force and an inertial force must be taken into account as well as the spring force. The damping force is proportional to the velocity $\dot{x}$ and is described with the damping coefficient p . The inertial force is proportional to the acceleration $\ddot{x}$. The oscillatory (resonant) system is described by the following equation:

(4) $F = ma = cx + p\dot{x} + m\ddot{x}$.



If negligible friction ($p \approx 0$) is presumed, the system resonates at the natural frequency ω_0 :

$$(5) \quad \omega_0 = \sqrt{\frac{c}{m}}.$$

Thus, according to equation (3), the measurement sensitivity S is directly linked to the resonant frequency ω_0 in the following manner:

$$(6) \quad S \omega_0^2 = 1.$$

In other words, it can be expected that sensitivity is reduced to a factor of $\frac{1}{4}$ when the resonant frequency is increased by a factor of 2. It is only below their resonant frequency that such spring-mass systems display adequate proportionality between measured variable and excursion.

Position-controlled sensor

Position-measuring systems also permit the use of the compensation method in which the system excursion caused by acceleration is compensated for by an equivalent restoring force (Figure 1b). In practical terms the system then ideally always operates very close to its zero point (high linearity, minimum cross sensitivity, high temperature stability). These position-controlled systems also have, on account of their control, higher stiffness and cutoff frequency than excursion systems of the same kind. Any lack of mechanical damping can be electronically generated here.

System behavior

In non-position-controlled systems the damping and resonance of the systems play key roles in system behavior. The application of Lehr's damping ratio D has proved effective in describing this behavior:

$$(7) \quad D = \frac{p}{m} \cdot \frac{1}{2\omega_0}.$$

Equation (4) can then be formulated as

$$(8) \quad \frac{F}{m} = \ddot{x} + 2\omega_0 D \dot{x} + \omega_0^2 x.$$

Using the dimensionless variable D permits a simple comparison to be made of different oscillatory systems: transient response and resonant response are defined to a large extent by this damping ratio.

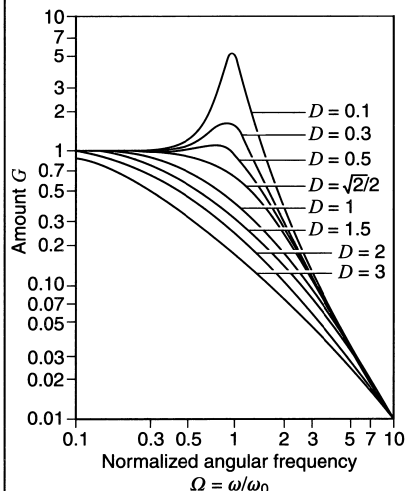
With very low damping ($D \rightarrow 0$) the system exhibits a resonance sharpness at ω_0 . This is often unwelcome in that on the one hand it can lead to the system being destroyed and on the other hand it results in a nonuniform transfer function ($G \gg 1$).

As damping factors increase, the system's resonance sharpness continues to decrease. While no more resonance sharpness is obtained under periodic excitation for damping factors $D = \sqrt{2}/2$ (Figure 2), any oscillating transient condition in the case of a step excitation disappears for factors $D > 1$.

In order to achieve as uniform a system response as possible in the region $G \approx 1$ over a wide frequency range, it is important when designing the system to define its damping precisely. Ideally this is influenced for example only slightly by

Figure 2: Amplitude-resonance curve

G Transfer function,
 D Damping,
 ω Angular frequency,
 ω_0 Resonant frequency,
 Ω Normalized angular frequency.



fluctuations in temperature. In practice sensors are therefore often designed in the range $D = 0.5 \dots 1.0$.

Mechanical stress-measuring systems

The piezoelectric effect can also be utilized to measure an acceleration. In this case the exertion of force by the external acceleration causes a mechanical stress in the piezoelectric material. These piezoelectric materials generate a charge Q under the influence of a force F on its surfaces, which are fitted with electrodes (Figure 3). This charge is proportional to the mechanical stress generated by the force.

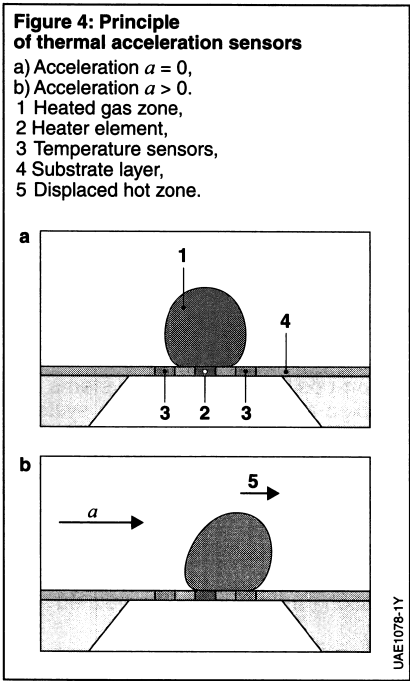
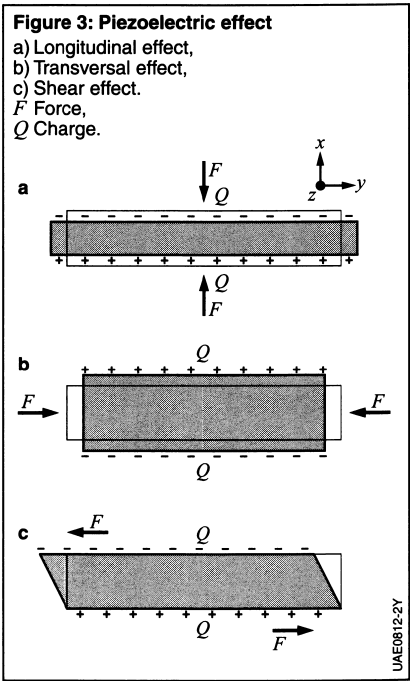
For use as a sensor the generated charges are discharged via the external resistor of a measuring circuit or via an internal resistor of the sensor. The sensor therefore can measure dynamically, but not statically. The typical cutoff frequency is above 1 Hz.

The piezoelectric effect is utilized for example in piezoceramic bimorphous spring elements and in piezoelectric knock sensors.

Thermal acceleration sensors

These sensors generate a confined heated gas zone (Figure 4). The gas in this zone has a lower density than the surrounding cooler gas. During an acceleration the low-density gas zone moves within the surrounding cooler gas. The resulting asymmetry can be sensed by temperature sensors which are interconnected in a bridge circuit. The bridge voltage constitutes the acceleration signal.

This principle is used in numerous applications such as for example rollover sensing, the driving-dynamics control, and even in smart phones.



Applications

Piezoelectric acceleration sensors

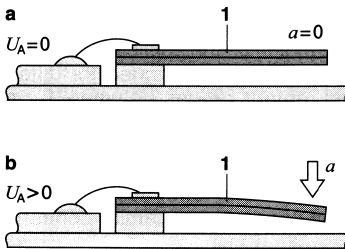
Piezoelectric bimorphous spring elements or two-layer piezoceramics (Figure 5) are used for restraint-system sensors for triggering seat-belt tighteners, airbags, and rollover bars. Their intrinsic mass causes them to deflect under acceleration to provide a dynamic (not DC response pattern) signal with excellent processing characteristics (typical cutoff frequency: 10 Hz). The sensor element is located in a sealed housing shared with the initial signal-amplification stage. It is sometimes encased in gel for physical protection. It consists of two oppositely polarized piezoelectric layers which are bonded to each other (bimorphous). An acceleration acting on it causes a mechanical tensile stress ($\epsilon > 0$) in one layer and a compressive stress ($\epsilon < 0$) in the other layer. The metallic layers on the upper and lower sides of the spring element serve as electrodes via which the resulting voltage is tapped.

This structure is packed together with the evaluation electronics in a hermetically sealed housing. The electronic circuit consists of an impedance transformer and an adjustable amplifier with specified filter characteristic.

The sensor's actuating principle can also be inverted: The sensor can be checked with an additional actuator electrode (on-board diagnosis).

Figure 5: Piezoelectric sensor

- a) At rest,
b) Subject to acceleration a .
1 Piezoceramic bimorphous spring element.
 U_A Measurement voltage.



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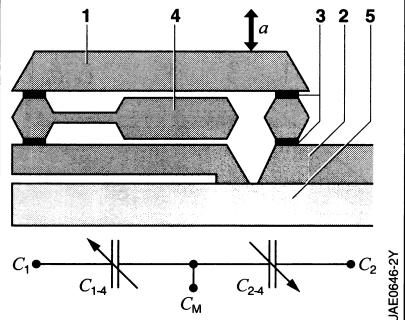
Micromechanical bulk silicon acceleration sensors

The first generation of micromechanical sensors relied on anisotropic and selective etching techniques to fabricate the required spring-mass system from the full silicon wafer (bulk silicon micromechanics) and produce the spring profile (Figure 6).

Capacitive taps have proven especially effective for the high-precision measurement of this seismic-mass deflection. This design entails the use of supplementary silicon or glass wafers with counter-electrodes above and below the spring-held seismic mass. This leads to a 3-layer structure, whereby the wafers and their counter-electrodes also provide overload protection. This layout corresponds to a series connection of two capacitors (C_{1-M} and C_{2-M}). Alternating voltages are supplied at the connections C_1 and C_2 , the superposition of these voltages is tapped at C_M , i.e. at the seismic mass. In the rest state the capacitances C_{1-M} and C_{2-M} are ideally equal. When an acceleration a acts in the measurement direction, the silicon center wafer is deflected as the seismic

Figure 6: Bulk silicon acceleration sensor

- 1 Silicon upper wafer,
2 Silicon lower wafer,
3 Silicon oxide,
4 Silicon center wafer M (seismic mass),
5 Glass substrate.
 a Acceleration,
 C Measurement capacitances.



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mass. The change in distance between the upper and lower wafers gives rise to a change in capacitance in the capacitors C_{1-M} and C_{2-M} , and thus a difference ΔC that is proportional to the applied acceleration. This in turn changes the electrical signal at C_M , which is amplified and filtered in the evaluation electronics.

Filling the sensor's hermetically sealed oscillatory system with a precisely metered charge of air leads to a very space-saving, inexpensive form of damping which also exhibits low temperature sensitivity.

This type of sensor is mainly used for low-level accelerations ($< 2g$) and relies upon a two-chip concept (sensor chip + CMOS processing chip).

Surface-micromechanical acceleration sensors

Surface-micromechanical sensors (SMM) have more compact dimensions than bulk silicon sensors. In SMM technology an additive process is employed to construct the spring-mass system on the surface of

the silicon wafer (Figure 7). In the sensor core the seismic mass with its comb-shaped electrodes is connected by spring elements to anchor points of the silicon oxide. The chip features fixed, also comb-shaped electrodes on both sides of these moving electrodes. The fixed and moving electrode fingers create individual capacitances which are connected in parallel. This produces an effective total capacitance of 300 fF up to 1 pF. Two rows of electrode fingers connected in parallel produce two useful capacitances (C_1-C_M and C_2-C_M), which change in opposite directions when the seismic mass is deflected. The spring-mass system is subjected during an acceleration to a deflection which behaves linearly to the acceleration via the spring restoring force. An electrical output signal that is linearly dependent on the acceleration can be obtained by evaluation of this differential capacitor.

Because of the low capacitance of typically 1 pF the evaluation electronics are therefore integrated together with the sensor on the same chip, or very closely connected to it on the same substrate or leadframe. The raw signal is amplified, filtered, and conditioned for the output interface. Analog voltages, pulse-width-modulated signals, SPI protocols (Serial Peripheral Interface) or PSI5 protocols (current interfaces, see PSI5) are usual for this purpose.

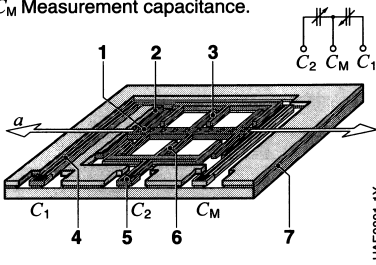
The mechanical and electrical signal paths of the sensor can be checked with a self-test function. The sensor structure is deflected by means of an electrostatic force (simulation of an acceleration) and the resulting sensor signal is compared with a setpoint value.

Depending on the applications, the sensor elements are designed for different measurement ranges between 1 g and 500 g. Initially these sensors were used for high acceleration rates (50...100 g, for passenger-protection systems), but are now also used for lower acceleration rates (e.g. for the driving-dynamics control).

Figure 7: Surface-micromechanical acceleration sensor with capacitive tap

- 1 Spring-mounted seismic mass with electrodes,
- 2 Spring,
- 3 Fixed electrodes with capacitance C_1 ,
- 4 Printed aluminum conductor (for self-test function),
- 5 Bond pad,
- 6 Fixed electrodes with capacitance C_2 ,
- 7 Silicon oxide.

a Acceleration in sensing direction,
 C_M Measurement capacitance.



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Piezoelectric knock sensor

The knock sensor is in principle a vibration sensor. It senses structure-borne sound vibrations that occur as "knocking" in a gasoline engine during uncontrolled combustions (Figure 8). The structure-borne sound vibrations must be able to be introduced from the measuring location on the engine block undamped and without resonance into the knock sensor. A suitable measuring point and a fixed screw connection are required for this purpose.

The knock sensor is screwed to the engine block (Figure 9). A seismic mass exerts as a result of its inertia pressure forces in time with the exciting vibrations on an annular piezoceramic element. These forces induce a charge transfer within the ceramic element. This generates between the upper and lower sides of the ceramic element a voltage that is tapped via contact disks. The knock signal generated in the sensor is forwarded to the engine ECU, where it is conditioned and evaluated.

When knocking noises are detected the engine ECU retards the ignition timing and thus counteracts any further knocking (see Knock control). The vibration frequency is typically 5 to 25 kHz.

Figure 9: Knock sensor (design and mounting)

- 1 Annular piezoceramic element,
 - 2 Seismic mass with pressure forces F ,
 - 3 Housing,
 - 4 Screw,
 - 5 Contact,
 - 6 Electrical connection,
 - 7 Engine block.
- V Vibration.

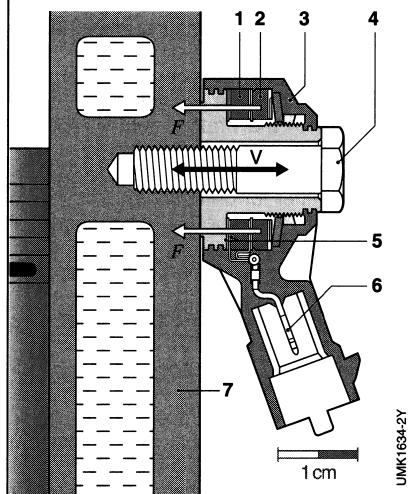
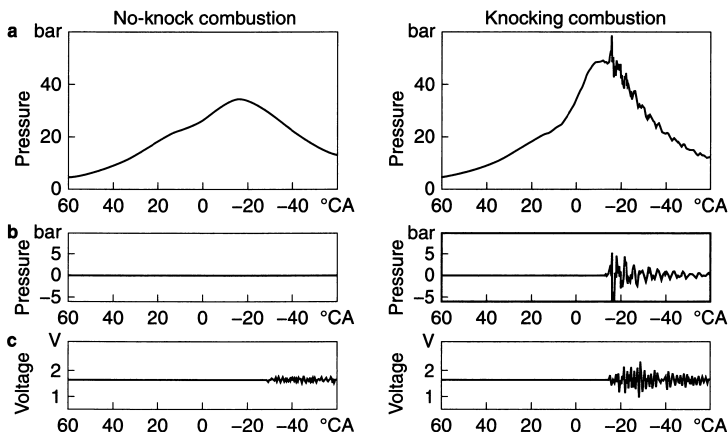


Figure 8: Pressure characteristic in the combustion chamber and corresponding knock-sensor signals

- a) Typical characteristic of combustion-chamber pressure (measured on a test engine),
- b) Bandpass-filtered signal of combustion-chamber pressure,
- c) Structure-borne noise signal sensed by the knock sensor.



Pressure sensors

Measured variables

The measured variable pressure is defined as a nondirectional force acting in all directions which occurs in gases and liquids. It still propagates very well in gelatinous substances and soft sealing compounds. The most important measured pressures in a motor vehicle are:

- Intake-manifold pressure and charge-air pressure (1 to 6 bar),
- Ambient pressure (approx. 1 bar), e.g. for boost-pressure control,
- Vacuum in the brake booster (approx. 1 bar relative to atmosphere),
- Differential pressure at the diesel particulate filter for detecting the filter-load state and leaks (up to 1 bar differential pressure),
- Brake pressure (10 bar) in electropneumatic brakes,
- Air-spring pressure (16 bar) for vehicles with air suspension,
- Tire pressure (5 bar absolute) for monitoring tire pressure,
- Hydraulic reservoir pressure (approx. 200 bar) for the antilock braking system and power steering,
- Shock-absorber pressure (200 bar) for chassis-control systems,
- Refrigerant pressure (35 bar) in air-conditioning systems,
- Modulation pressure (35 bar) in automatic transmissions,
- Fluid pressure for clutch actuation in double-clutch transmissions (20 bar),
- Engine-oil pressure for demand-controlled oil pumps (10 bar),
- Brake pressure in brake master and wheel-brake cylinders (200 bar) and for automatic yaw-moment compensation in electronically controlled brakes,
- Positive and vacuum pressure in fuel tank (0.5 bar) for on-board diagnosis,
- Combustion-chamber pressure (100 bar, dynamic) for misfiring and knock detection,
- Pump-side pressure in diesel distributor-type injection pumps (up to 1,000 bar, dynamic) for electronic governing,

- Fuel pressure in the low-pressure circuit for demand-controlled fuel pumps (diesel and gasoline; 10 bar),
- Rail pressure in LPG and CNG systems (4 to 16 bar),
- Rail pressure for diesel common rail (up to 2,700 bar),
- Rail pressure for gasoline direct injection (up to 280 bar),
- Oil pressure for taking into account the engine load in the service display.

Measurement principles

Dynamically and statically acting pickups or sensors are used to measure pressures. Dynamically acting pressure sensors include for example microphones, which are insensitive to static pressures and are only used to measure pressure pulsations in gaseous or liquid media. Since up to now, practically only static pressure sensors have been used in automobiles, these will be dealt with in more detail here. Static pressure measurement is effected directly by the deformation of a diaphragm.

Diaphragm-type sensors

Design

The most common method used for pressure measurement (also in automotive applications) uses a thin diaphragm as the intermediate stage. The pressure to be measured is first of all applied to one side of this diaphragm so that this bends to a greater or lesser degree as a function of the pressure (Figure 1a). Within a very wide range, its diameter and thickness can be adapted to the particular pressure range. Low-pressure measuring ranges lead to comparatively large diaphragms which can deform in the range from 0.01 to 1 mm. Higher pressures demand thicker, low-diameter diaphragms which only deform very slightly by a few micrometers.

To be precise, a diaphragm's deformation depends upon the difference in the pressure applied to its top and bottom sides. Accordingly, there are three different basic types of pressure sensor:

- Absolute-pressure sensors,
- Differential-pressure sensors,
- Relative-pressure sensors.

Relative-pressure sensors measure the differential pressure relative to the ambient pressure.

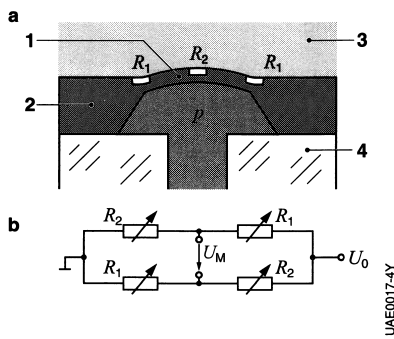
Voltage-measuring methods dominate in all pressure ranges and here in practical terms only strain-gage technology is used.

Strain-gage technology

The strains on the diaphragm when a diaphragm-type sensor is subjected to deformation are sensed by strain gages (strain-gage resistors) which are applied to the diaphragm (e.g. diffused or vapor-deposited) (Figure 1a). Under the influence of mechanical stresses their electrical resistance changes on account of the piezoresistive effect. The K factor (gage factor) specifies the relative change of the strain-gage resistor referred to the relative change of its length. For the resistors diffused into the monocrystalline silicon in micromechanical pressure sensors this factor is especially high, typically $K \approx 100$.

Figure 1: Semiconductor absolute-pressure sensor

- a) Cutaway view,
- b) Wheatstone-bridge circuit.
- 1 Diaphragm,
- 2 Silicon chip,
- 3 Reference vacuum,
- 4 Glass (Pyrex),
- p Measured pressure,
- U_0 Supply voltage,
- U_M Measurement voltage,
- R_1 Strain-gage resistor (compressed),
- R_2 Strain-gage resistor (stretched).



The resistors are interconnected to form a Wheatstone bridge (Figure 1b). The diaphragm is deformed to varying degrees depending on the effective pressure; in the process two resistors are stretched and two resistors are compressed. This alters their electrical resistance and thus also the measurement voltage (bridge voltage). The measured voltage is a measure of the pressure. This circuit produces a higher measurement voltage than is the case when a single resistor is evaluated. The Wheatstone bridge thus provides for a highly sensitive sensor.

Applications

Micromechanical pressure sensors

Micromechanical pressure sensors are used for pressure ranges of less than 6 bar (in low-pressure sensors) and for pressure ranges of less than 70 bar (in medium-pressure sensors).

The measuring cell of the micromechanical pressure sensor consists of a silicon chip in which a thin diaphragm is micro-mechanically etched (Figure 1). Four resistors arranged in a Wheatstone-bridge circuit are diffused on the diaphragm (see above). The bridge voltage is a measure of the pressure on the diaphragm.

The bridge signal must still be linearized and amplified. Temperature effects must also be compensated. This is performed either in a circuit integrated on the measuring chip or in a separate ASIC (application-specific integrated circuit). The output signal can be transferred either in the form of an analog voltage (0 to 5 V) or in digital form, e.g. via the SENT interface.

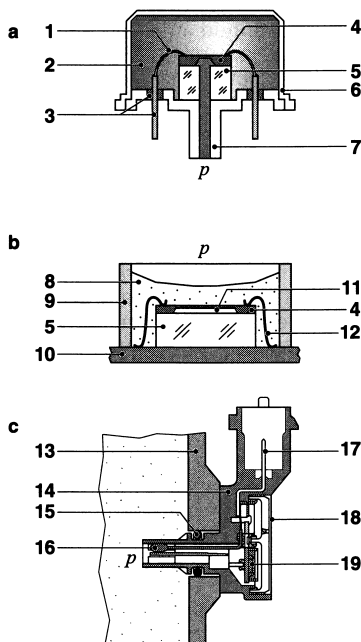
The advantage of digital transfer protocols over analog signals is that interface tolerances (contact and cable resistances) play no role and that as a rule additional information (fault codes, temperature signals, etc.) can still be transferred.

In the case of sensors for very aggressive or liquid measured media (e.g. for fuel-pressure and charge-air pressure sensor) "reverse assembly" is often used in which the measured pressure is conducted to an electronically passive cavity recessed into the side of the sensor

Figure 2: Absolute-pressure sensor

- a) Reverse assembly
(reference vacuum on structure side),
b) Simplified assembly with protective gel,
c) "Outer packaging"
for intake-manifold installation
with integrated air-temperature sensor.

- 1,3 Electrical connections
with glass-enclosed lead-in,
2 Reference-vacuum chamber,
4 Measuring cell (chip)
with evaluation electronics,
5 Glass base,
6 Cap,
7 Supply for measured pressure p ,
8 Protective gel,
9 Gel frame,
10 Ceramic hybrid,
11 Cavity with reference-vacuum chamber,
12 Bonded connection,
13 Manifold wall,
14 Housing,
15 Sealing ring,
16 Temperature sensor,
17 Electrical connection,
18 Housing cover,
19 Measuring cell.
 p Measured pressure.



chip (Figure 2a). For maximum protection, the – much more sensitive – side of the chip with the measuring resistors, evaluation electronics and contacts is enclosed in a reference-vacuum chamber located between the housing's base and the soldered metal cap.

However, a cheaper arrangement is to seat the silicon chip with etched diaphragm and four strain-gage resistors as a measuring cell on a glass base. The reference-vacuum chamber is located in a cavity between the diaphragm and the glass base (Figure 2b). Alternatively, measuring chips made of porous silicon with an enclosed reference-vacuum chamber can be used for absolute-pressure sensors. The silicon chip is subjected to pressure from the side on which the measuring resistors and the evaluation electronics are located. This sensitive side of the chip is protected by a suitable gel against the pressure medium. The compact design of integrated single-chip sensors means that they are suitable for mounting directly on the intake manifold (Figure 2c).

Low-pressure sensors

This design is used in virtually all low-pressure sensors (maximum pressure less than 6 bar) such as for example charge-air pressure sensors and barometric sensors. For differential-pressure sensors (e.g. for diesel particulate filters or brake boosters) both sides of the diaphragm are subjected to the pressure medium.

These sensors can also be used in tire-pressure monitoring systems. Measurement will be continuous and non-contacting.

Medium-pressure sensors

The range of medium-pressure sensors is essentially described by a maximum pressure-measuring range of approx. 6 to 70 bar. These sensors are used to measure engine-oil pressure, fuel pressure ahead of the high-pressure pump, hydraulic pressure in automatic transmissions (torque-converter, double-clutch, and CVT transmissions), to measure pressure in LPG and CNG systems, and to measure pressure in air-conditioning systems.

The wide variety of applications means that there is a broad range of mechanical and electrical interfaces. The sensors are screwed into lines or into the crankcase and transmission case. A metallic taper seal has proven effective, but O-rings and sealing rings are also used. The design of the medium-pressure sensor very much follows that of the high-pressure sensor, with the metal diaphragm being replaced by a silicon-micromechanics-technology sensor element. In this case the sensor elements used in low-pressure sensors have been adapted by optimized etching methods for higher pressures and increased bursting-pressure strength. Here too the measurement signal of a Wheatstone-bridge circuit is evaluated. The sensor signal is conditioned and issued as an analog or a digital output signal. This is done either integrated in a silicon chip (1-chip technology) or by measuring element and evaluation ASIC (2-chip technology).

Combined sensors for pressure and temperature are used in some applications (e.g. in the engine oil-level sensor). For this purpose an NTC is integrated in the threaded fitting and the thermistor of the NTC is evaluated in the ECU by suitable circuits. The SENT protocol offers the opportunity to issue the pressure and temperature signals in a joint output signal. This dispenses with the need for a separate line for the temperature signal.

High-pressure sensors with metal diaphragm

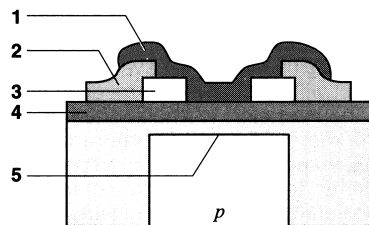
Diaphragms made of high-quality spring steel are used at very high pressures as have to be measured for example in the rail of the common-rail system or gasoline direct injection for closed-loop control (Figures 3 and 4). Further applications include braking systems such as the anti-lock braking system and driving-dynamics control, and also industrial hydraulics.

Four thin-film strain gages are applied to the diaphragm; the measurement principle is the same as for micromechanical pressure sensors. The steel diaphragm insulates the measured medium, differs from silicon in retaining a yield range for enhanced burst resistance, and is easy to install in metallic housings.

Insulated sputtered (vapor-deposited) metallic thin-film strain gages ($K \approx 2$) and even polysilicon strain gages ($K \approx 40$) offer permanently high sensor accuracy. Amplification, calibration, and compensation elements can be combined in a single ASIC, which is then integrated together with the required EMC protection on a small carrier in the sensor housing.

Figure 3: High-pressure sensor with metal diaphragm, measuring element

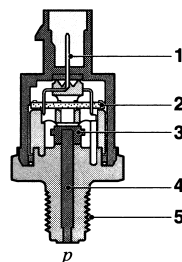
- 1 SiN_x passivation,
 - 2 Gold contact,
 - 3 Polysilicon strain-gage resistor,
 - 4 SiO_2 insulation,
 - 5 Steel diaphragm.
- p Measured pressure.



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Figure 4: High-pressure sensor with metal diaphragm, design

- 1 Electrical connection (plug),
 - 2 Evaluation circuit,
 - 3 Steel diaphragm with strain-gage resistors,
 - 4 Pressure connection,
 - 5 Fastening thread.
- p Measured pressure.



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Temperature sensors

Measured variables

Temperature is defined as a nondirectional quantity which characterizes the energy state of a given medium, and which can be a function of time and location.

- (1) $T = T(x, y, z, t)$,
 x, y, z Space coordinates,
 t Time,
 T measured according to the Celsius or Kelvin scale.

In the case of gaseous and liquid measured media, it is generally possible to measure temperature at all points without any problems; in the case of solid bodies, measurement is usually confined to the surface. The temperature sensors mostly commonly used need to have direct, close contact with the measured medium (contact thermometer) to enable them to assume the medium temperature as precisely as possible. Outside temperature, intake-air temperature, and exhaust-gas temperature are examples of temperature measurement of gaseous media. Coolant temperature and engine-oil temperature are examples of temperature measurement of liquid media. Further areas of application of temperature measurement in vehicles are shown in Table 1. They can dif-

fer greatly in terms of required measuring accuracy and permissible measuring time.

For special cases non-contact temperature sensors are also used which determine the temperature of a body or a medium on the basis of the (infrared) heat radiation emitted by it (radiation thermometer, pyrometer, thermal imaging camera). These temperature sensors are used in night-vision systems (see Far-infrared systems) and for pedestrian recognition with infrared cameras.

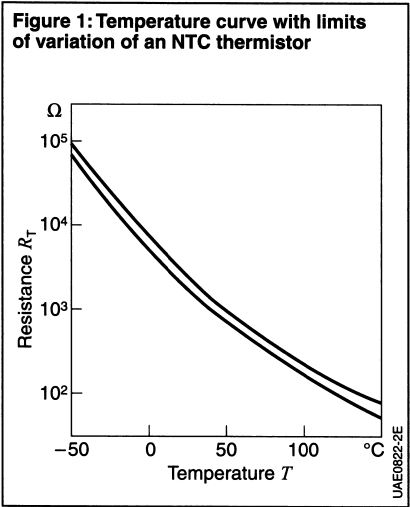
At many locations temperature is also measured as a secondary variable in order that it can be compensated in cases where temperature variations trigger faults or act as an undesirable influencing variable – for example in sensors for other physical variables whose measured value is to depend as little as possible on the temperature.

Measurement principle

Temperature measurements in motor vehicles are conducted almost entirely by exploiting the sensitivity to temperature variation found in electrical resistance materials with a positive temperature coefficient (PTC, NTC thermistor) or with a negative temperature coefficient (NTC, PTC thermistor) as contact thermometers. Depending on the temperature, the sensor exhibits a certain resistance

Table 1: Temperature ranges in motor vehicles

Measuring point	Range in °C
Intake and charge air	−40...170
Outside atmosphere	−40...60
Passenger compartment	−20...85
Ventilation & heating air	−20...60
Evaporator (air conditioner)	−10...50
Coolant	−40...130
Engine oil	−40...170
Battery	−40...100
Fuel	−40...120
Tire air	−40...120
Exhaust emissions	100...1,000
Brake calipers	−40...2,000



value (Figure 1). Conversion of the resistance variation into an analog voltage is performed predominantly by adding a temperature-neutral or inversely sensitive resistance to a voltage divider (Figure 2a) or by supplying an injected current (Figure 2b). For the voltage-divider circuit the following is obtained

$$U_A(T) = U_0 \frac{R(T)}{R(T) + R_V}.$$

With the injected current I_0 the measurement voltage is obtained at

$$U_A(T) = I_0 R(T).$$

The voltage measured at the measuring resistor is thus temperature-dependent. This analog voltage is digitized in the ECU by an analog-digital converter and then assigned via a characteristic curve to a temperature value.

Alternatively, signal processing can also be performed by an evaluation circuit integrated in the sensor; the temperature value is then transferred via a digital interface (see PS15).

Sensor types

Sintered-ceramic resistors (NTC)

Semiconducting sintered-ceramic resistors made of heavy-metal oxides and oxidized mixed crystals (sintered in pearl

or plate form) display an exponentially falling temperature curve (Figure 1). It can be described to good approximation by the following exponential equation:

$$R(T) = R_0 e^{\frac{B}{T} - \frac{1}{T_0}},$$

where

$$R_0 = R(T_0),$$

$$B = 2,000 \dots 5,000 \text{ K},$$

T Temperature in K.

The resistance value can vary up to five powers of ten, for example typically from some 100 kilohms to some 10 ohms. High thermal sensitivity means that applications are restricted to a "window" of approximately 200 K; however, this range can be defined within a latitude of -40°C to approximately 850°C by selecting an appropriate NTC. Close tolerances of $\pm 0.5 \text{ K}$ at a selectable reference point are possible for example by means of read-out, but this is also reflected in the cost.

Thin-film metallic resistors (PTC)

Thin-film metallic resistors, integrated on a single substrate wafer (e.g. by vapor-depositing or sputtering) with two supplementary, temperature-neutral trimming resistors (Figure 3a), are characterized by extreme precision, as they can be manufactured and then "trimmed" with lasers to maintain exact response-curve tolerances over long periods of time (Figure 3b). Here the values of the trimming resistor connected in series to the measuring resistor and of the trimming resistor connected in parallel are changed.

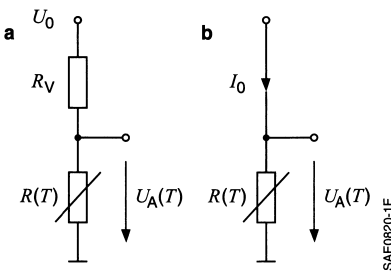
The use of layer technology makes it possible to adapt the substrate (ceramic, glass, plastic foil) and the upper layers (plastic molding or paint, sealed foil, glass and ceramic coatings) to the respective application, and thus provide protection against the monitored medium.

Although metallic layers are less sensitive to thermal variations than the ceramic-oxide semiconductor sensors, both linearity and reproducibility are better. The following formulation is used to provide the computational description:

$$R(T) = R_0 (1 + \alpha \Delta T + \beta \Delta T^2 + \dots)$$

Figure 2: Resistance-measurement methods

- a) Voltage-divider circuit,
- b) Measurement with injected current.
- U_0 Supply voltage,
- I_0 Injected current,
- R_V Voltage-divider resistor,
- $R(T)$ Measuring resistor,
- $U_A(T)$ Measurement voltage.



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where
 $\Delta T = T - T_0$,
 $T_0 = 20^\circ\text{C}$ (reference temperature),
 α Linear temperature coefficient,
 β Quadratic temperature coefficient.

The coefficient β is small for metals, but not entirely negligible. Therefore in sensors of this type the measurement sensitivity is characterized with a mean temperature coefficient, “TC 100”. It corresponds to the mean characteristic-curve gradient between 0°C and 100°C (Figure 4) and is obtained from the following relationship:

$$\text{TC 100} = \frac{R(100^\circ\text{C}) - R(0^\circ\text{C})}{R(0^\circ\text{C}) \cdot 100\text{ K}} = \alpha_{100}.$$

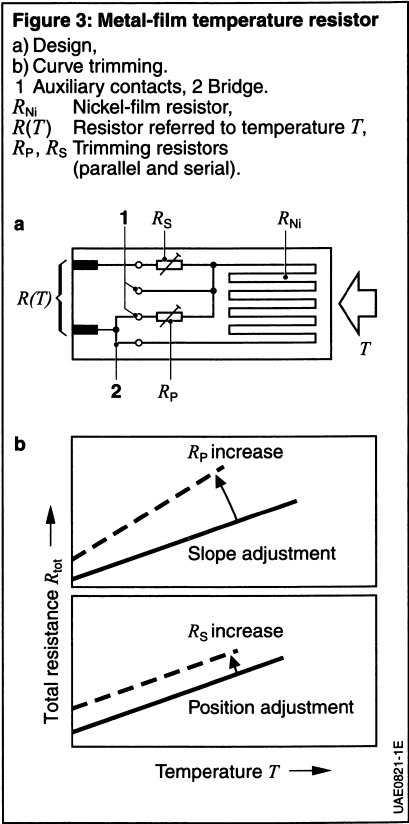


Table 2 shows the mean temperature coefficients for some metals.

Metal-film resistors are generally manufactured and marketed with a basic value (resistance value at 20°C) of $100\ \Omega$ or $1,000\ \Omega$ (e.g. under the designation Pt 100 or Pt 1000) in different tolerance classes. Platinum resistors (Pt) do have the lowest temperature coefficient, but are very accurate and resistant to aging.

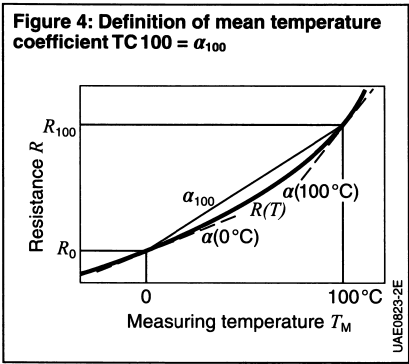
In addition to compensating elements, further active and passive circuit elements for the thin-film sensor can basically be integrated on the carrier chip. This facilitates initial, advantageous signal conditioning and conversion at the measuring point.

Thick-film resistors (PTC and NTC)

Thick-film resistors consist of a carrier chip (e.g. thin ceramic wafer) on which the resistor material is applied as paste (e.g.

Table 2: Mean temperature coefficient of some metals

Sensor material	TC 100	Measurement range
Nickel (Ni)	$6.18 \cdot 10^{-3}/\text{K}$	$-60 \dots 250^\circ\text{C}$
Copper (Cu), value dependent on composition	$3.8 \cdot 10^{-3}/\text{K}$ up to $4.3 \cdot 10^{-3}/\text{K}$	$-50 \dots 200^\circ\text{C}$
Platinum (Pt) (DIN EN 60751, [1])	$3.85 \cdot 10^{-3}/\text{K}$	$-200 \dots 850^\circ\text{C}$



metal oxide) using thick-film technology and sintered at 800 °C to the substrate.

Thick-film resistors with their higher resistivity (low surface-area requirement) and positive and negative temperature coefficients are generally employed as temperature sensors for compensation purposes. They have nonlinear response characteristics (without, however, the extreme variations of the massive NTC resistor) and can for example be laser-trimmed. The measurement effect can be enhanced by using NTC and PTC materials to form voltage-divider circuits.

Monocrystalline silicon semiconductor resistors (PTC)

When monocrystalline semiconductor materials, such as silicon, are used to manufacture the temperature sensor, it is possible to integrate additional active and passive circuitry on the sensor chip. This facilitates initial signal conditioning at the measuring point. Due to the closer tolerancing which is possible, the measuring element is manufactured according to the "spreading-resistance" principle. The current flows through the measuring resistor and through a surface-point contact before arriving at the silicon bulk material. It then proceeds, widely distributed, to a counter-electrode covering the base of the sensor chip (Figure 5).

As well as the highly reproducible material constants, the high current density after the contact point (high precision achieved through photolithographic manufacture) almost exclusively determines the sensor's resistance value. To eliminate polarity sensitivity the sensors are mostly series-connected in a pair in opposite alignment (double-hole version, Figure 5). The bottom electrode can then be designed as a metallic temperature contact (with no electrical function).

Measurement sensitivity is practically double that of a platinum resistor ($TC_{100} = 7.73 \cdot 10^{-3}/K$). However, the temperature-response curve is less linear than that of a metallic sensor. The measuring range is limited to approximately 150 °C by the material's intrinsic conductivity.

Applications in motor vehicles

These temperature sensors are used in many motor-vehicle applications. Here are some examples:

- Coolant-temperature sensor,
- Fuel-temperature sensor,
- Engine-oil temperature sensor,
- Intake-air temperature sensor,
- Charge-air temperature sensor,
- Outside-temperature sensor,
- Interior-temperature sensor,
- Exhaust-gas temperature sensor, etc.

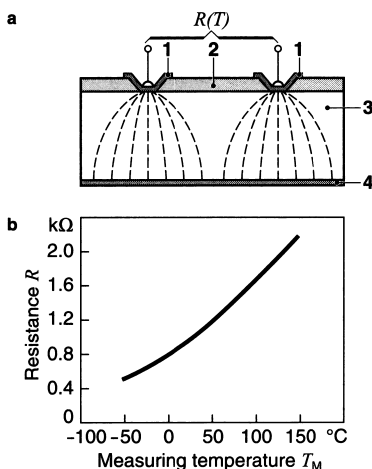
References for temperature sensors

[1] DIN EN 60751: Industrial platinum resistance thermometers and platinum temperature sensors.

Figure 5: Silicon semiconductor resistor (spreading-resistance principle)

- a) Design,
b) Characteristic curve.

- 1 Contacts,
2 Passivation (nitride, oxide),
3 Silicon substrate,
4 Counter-electrode without connection,
 $R(T)$ Thermistor.



Torque sensor

Measured variables and application

Torque measurement is utilized in a variety of applications in motor vehicles. Torque sensors are used for example to sense the steering torque initiated by the driver.

Electromechanical power-steering systems are increasingly being used in vehicles. The essential benefits are simple installation and start-up in the vehicle, energy saving, and the suitability of these systems in the vehicle's ECU network for assistance systems to increase comfort and safety.

Measurement principle

When it comes to torque measurement, there are two different methods: angle and stress measurement. In contrast to stress-measurement methods (with strain gages), angle-measurement methods require a certain length of the torsion bar over which the torsion angle can be picked off.

To sense the driver command, it is necessary in an electromechanical power-steering system to measure the torque initiated by the driver. The sensors currently used in series production incorporate in the steering shaft a torsion bar which in the course of a steering torque applied by the driver undergoes a defined torsion linear to the initiated torque (Figure 1). The torsion is in turn measured by appropriate means and converted into electrical signals. The required measurement range of a torque sensor for use in an electromechanical power-steering system is usually around ± 8 to ± 10 Nm. The maximum torsion angle is mechanically limited by carrier elements to protect the torsion bar against overload and destruction.

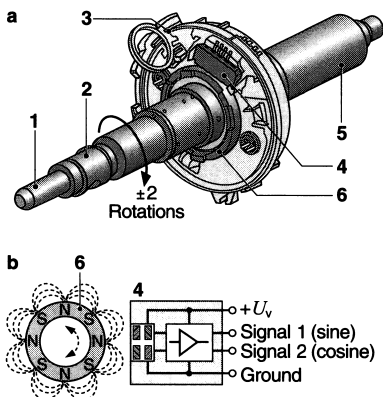
To be able to measure the torsion and thus the applied torque, a magnetoresistive sensor is mounted on one side of the torsion bar which samples the field of a magnetic multipole wheel mounted on the other side. The number of poles on

this wheel is chosen so that the sensor outputs a clear signal within its maximum measurement range to provide at all times a clear indication of the applied torque. The magnetoresistive sensor used supplies over the measurement range two signals which describe a sine signal and a cosine signal when shown against the torsion-bar torsion angle. The torsion angle and thus the torque are calculated in an ECU with the aid of an arc-tangent function.

Because the two signals are always permanently assigned over the defined measurement range, in the event of a deviation from these signals sensor faults can be detected and the necessary substitute measures initiated.

Figure 1: Torque sensor

- a) Sensor module,
b) Measurement principle.
1 Torsion bar (torsion range internal),
2 Input shaft (from steering wheel),
3 Volute spring for electrical contacting,
4 Sensor module with magnetoresistive sensor chip and signal amplification,
5 Steering shaft,
6 Magnetic multipole wheel.

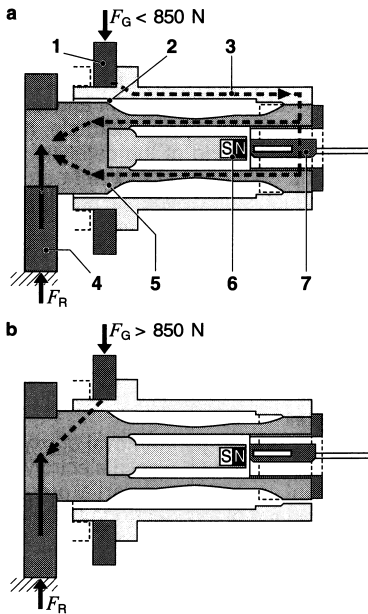


A volute spring with the required number of contacts is used to contact the sensor over the torsion range of approx. ± 2 steering-wheel turns. This volute spring serves to deliver the supply voltage and transmit the measured values.

Figure 2: Measurement principle of iBolt force sensor

- a) Conditions for $F_G < 850$ N
(inside the measurement range),
 - b) Conditions for $F_G > 850$ N
(outside the measurement range).
- 1 Swinging arm, 2 Air gap, 3 Sleeve,
4 Seat rail,
5 Double bending beam,
6 Magnet,
7 Hall IC.
 F_G Weight,
 F_R Bearing force.

The dashed lines indicate the flow of force in the force sensor.



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Force sensor

Measured variables and application

One application of force measurement in motor vehicles is the sensing of the front passenger's weight. Classifying the front passenger by measuring their weight enables the airbag to be deactivated when a small child is sitting in the seat.

Measurement principle

The operating principle of the iBolt sensor is based on measuring the deflection of a bending beam in response to the front passenger's weight. The extent of this deflection is detected by measuring the magnetic field strength with a Hall sensor (Figure 2a).

The sensor is designed in such a way that preferably the vertical component of the front passenger's weights causes a deflection of the bending beam. The magnet and the Hall IC are arranged in the sensor in such a way that the static magnetic field that penetrates the Hall IC produces an electrical signal linear to the deflection of the bending beam. The special design of the sensor prevents a horizontal deflection of the Hall IC in respect of the magnet in order to minimize the influence of transverse forces and torques. In addition, the maximum stress in the bending beam is limited by a mechanical overload stop (Figure 2b). This protects the sensor particularly in overload situations in the event of a crash.

The force generated by the front passenger's weight is directed from the upper seat structure via the sleeve into the bending beam (Figure 2a). The force is then directed from the bending beam into the lower seat structure. The bending beam is designed as a double bending beam as this has an S-shaped deformation line. Here the two vertical connecting points of the double bending beam remain vertical for the entire deflection range. This ensures a linear and parallel movement of the Hall IC in respect of the magnet, producing a linear output signal.

Gas and concentration sensors

λ sensors

Measurement principle

λ sensors measure the oxygen content in the exhaust gas. They are used to regulate the air/fuel ratio in motor vehicles. The name is derived from the excess-air factor λ . This factor indicates the ratio of the current air volume to the theoretical air volume which is required for a full combustion of the fuel. It cannot be determined directly in the exhaust gas, but only indirectly via the oxygen volume present in the exhaust gas or required to fully convert combustible components. λ sensors consist of platinum electrodes which are mounted on a ceramic solid electrolyte that conducts oxygen ions (e.g. ZrO_2).

The signal from all the λ sensors is based on electrochemical processes with the involvement of oxygen (see Electrochemistry). The platinum electrodes used catalyze the reaction of remnants of oxidizable components in the exhaust gas (CO , H_2 and hydrocarbons $\text{C}_x\text{H}_y\text{O}_z$) with exhaust-gas oxygen. λ sensors consequently measure not the real oxygen content in the exhaust gas, but instead that content which corresponds to the chemical equilibrium of the exhaust gas.

Applications

λ sensors are used in gasoline engines during the regulation of a stoichiometric mixture ($\lambda = 1$) to deliver the lowest-pollutant exhaust gas possible. Optimum impact by the three-way catalytic converter is guaranteed in this range.

Two-point λ sensors (step-change or switching-type sensors) indicate whether the mixture is rich ($\lambda < 1$, excess fuel) or lean ($\lambda > 1$, excess air). With these sensors the oxygen partial pressure of stoichiometric air/fuel mixtures can be measured very accurately due to the steep part of the sensor characteristic curve in this environment. Outside this environment, however, the characteristic curve is very flat (Figure 2).

Only the large measurement range of wide-band λ sensors (from $\lambda = 0.6$ to clean air) allow their use in systems with direct injection in stratified-charge operation and in diesel engines. λ control that can be achieved with wide-band λ sensors results in significant system and emission advantages over two-point control with a step-change sensor and further applications such as, for example, more accurate monitoring of the catalytic converter and controlled component protection. The high signal dynamic response of wide-band λ sensors with response times of less than 100 ms improves λ control.

Operating concept

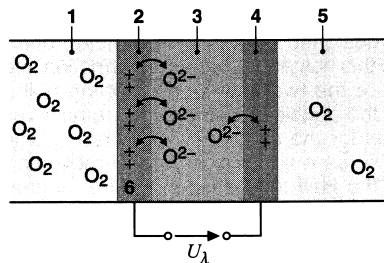
All the exhaust-gas sensors described in the following consist of two modules: Nernst cell and pump cells.

Nernst cell

The incorporation and removal of oxygen ions in the lattice of the solid electrolyte is dependent on the oxygen partial pressure on the surface of the electrode (Figure 1). Thus at low partial pressure more oxygen ions leave than enter. The vacant spaces in the lattice are reoccupied by advancing oxygen ions. An electric field is generated on account of the resulting charge separation at different oxygen partial pressures at the two electrodes. The electric field forces push advancing oxygen ions back and an equilibrium develops at the so-called Nernst voltage.

Figure 1: Nernst cell

- 1 Reference gas, 2 Anode,
 - 3 Solid electrolyte of Y-doped ZrO_2 ,
 - 4 Cathode,
 - 5 Exhaust gas,
 - 6 Residual charges on the anode.
- O^{2-} Oxygen ion,
 U_λ Sensor voltage (Nernst voltage).



Pump cell

When a voltage is applied that is less or greater than the developing Nernst voltage, this state of equilibrium can be changed and oxygen ions actively transported through the ceramic. This creates between the electrodes a current, borne by oxygen ions. Crucial to the direction and intensity is the difference between the applied voltage (pump voltage U_P) and the developing Nernst voltage. This process is called electrochemical pumping.

Two-point λ sensors

Design

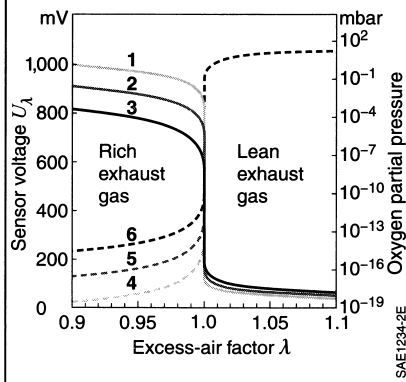
Two-point λ sensors indicate whether the mixture is rich ($\lambda < 1$, excess fuel) or lean ($\lambda > 1$, excess air). With these sensors the oxygen partial pressure of virtually stoichiometric air/fuel mixtures can be measured very accurately due to the steep part of the characteristic curve in this environment and the lowest-pollutant exhaust gas possible achieved by regulating the fuel quantity.

Figure 2: Characteristic curve of a two-point λ sensor at different sensor-element temperatures

U_λ Sensor voltage,
 $p_{A(O_2)}$ Oxygen partial pressure
 in the exhaust gas,

λ Excess-air factor.

- 1 U_λ at 500 °C,
- 2 U_λ at 700 °C,
- 3 U_λ at 900 °C,
- 4 $p_{A(O_2)}$ at 500 °C,
- 5 $p_{A(O_2)}$ at 700 °C,
- 6 $p_{A(O_2)}$ at 900 °C.



Operating concept

The operating concept is based on the principle of a Nernst cell (Figure 1). The useful signal is the Nernst voltage U_λ that develops between an electrode exposed to the exhaust gas and an electrode exposed to the reference gas. The characteristic curve is very steep at $\lambda = 1$ (Figure 2). In lean mixtures the Nernst voltage increases linearly with the temperature. In rich mixtures, on the other hand, the influence of temperature on the oxygen partial pressure predominates in the state of equilibrium. The higher the temperature, the higher this oxygen partial pressure.

The establishment of equilibrium at the exhaust-gas electrode is also the cause of very small deviations of the λ jump from the exact value. The exhaust-gas electrode is covered with a porous protective ceramic layer to protect against contamination and to encourage the establishment of equilibrium by limiting the number of arriving gas particles. Hydrogen and oxygen diffuse through the porous protective layer and are converted on the electrode. More oxygen must be available on the protective layer to ensure that the faster-diffusing hydrogen is fully converted on the electrode; in all there must be a slightly lean mixture in the exhaust gas. The characteristic curve is therefore shifted in the lean direction. This " λ shift" is electronically compensated during control.

To deliver the signal a reference gas is required that is separated (gas-tight) from the exhaust gas by the ZrO_2 ceramic. Figure 3 depicts the structure of a planar sensor element with reference-air passage. Ambient air is used as reference gas in this type. Figure 4 shows the element in the sensor housing. The exhaust-gas and reference-gas sides are separated from each other (gas-tight) by means of a packing seal. The reference-gas side in the housing is permanently supplied with reference air via the supply leads.

Systems with a "pumped" reference are increasingly being used as an alternative to reference air. Pumping refers here to the active transportation of oxygen in the ZrO_2 ceramic by injecting a current, in which the current is set so low that it does not interfere with the actual measurement. The reference electrode itself is connected via a tighter output in the element to the reference-gas chamber. This results in a build-up of excess oxygen pressure at the reference electrode. This system offers additional protection against unwanted gas components penetrating into the reference-gas chamber.

Robustness

The ceramic sensor element is protected by a protective tube ahead of the direct exhaust-gas flow (Figure 4). This contains openings through which only a small amount of the exhaust gas is directed to the sensor element. It prevents heavy thermal stresses from the exhaust-gas flow and at the same time provides mechanical protection for the ceramic element.

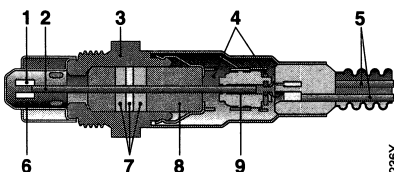
The housing must meet stringent temperature requirements, meaning that high-quality materials must be used. Temperatures in excess of $1,000^\circ\text{C}$ can

be recorded in the exhaust gas, as well as 700°C at the hexagon head and up to 280°C at the cable outlet. For this reason, only ceramic and metallic materials are used in the hot area of the sensor.

Most two-point λ sensors are also fitted with a heater element (Figure 3). This quickly heats (FLO, fast light-off) the sensor element to operating temperature and provides for fast control readiness.

Figure 4: Two-point λ sensor, sensor element in the housing

- 1 Protective tube,
- 2 Sensor element,
- 3 Hexagon head,
- 4 Reference gas,
- 5 Electrical supply lead,
- 6 Exhaust-gas side,
- 7 Packing seal,
- 8 Support ceramic,
- 9 Contacting.

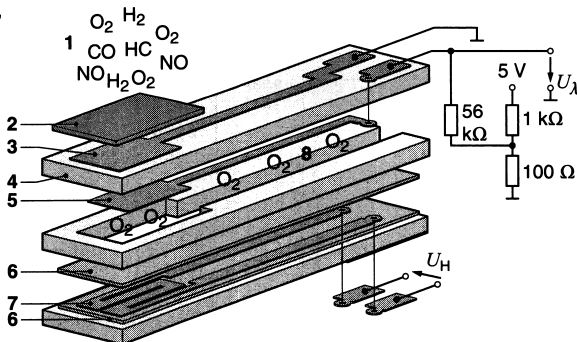


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Figure 3: Structure of a planar two-point λ sensor with protective circuit (exploded view)

The vertical lines symbolize conductive connections.

- 1 Exhaust gas,
 - 2 Porous protective layer,
 - 3 Outer electrode (platinum electrode),
 - 4 ZrO_2 ceramic with Nernst cell,
 - 5 Reference electrode (platinum electrode),
 - 6 Al_2O_3 insulation layer,
 - 7 Heater element,
 - 8 Reference air.
- U_λ Sensor voltage,
 U_H Heating voltage.



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In practice the λ sensor after engine starting is switched on only after a delay. Water that is produced as a combustion product and condenses again in the cold exhaust-gas system is transported by the exhaust gas and can reach the sensor element. If a droplet of this water touches a hot sensor element, it vaporizes immediately and abstracts a large amount of heat locally from the sensor element. The heavy mechanical stresses that occur as a result of thermal shock can cause the ceramic sensor element to break. For this reason, the sensor is often switched on only after the exhaust-gas system has been sufficiently heated. In more recent developments the ceramic elements are enclosed in a further porous, ceramic layer which significantly increases robustness against thermal shock. When a water droplet touches the elements, it spreads in the porous layer. Local cooling is spread over a wider area and mechanical stresses are reduced.

Protective circuit

Figure 3 shows the protective circuit of a two-point λ sensor. Because the sensor when cold cannot generate a signal due to the absence of conductivity of the ZrO_2 ceramic, it is connected via a resistor to a voltage divider. In the cold state the sensor signal is therefore 450 mV, the value of a stoichiometrically combusted gas ($\lambda = 1$). As the temperature increases the sensor is able to develop the Nernst voltage. After approximately 10 s the sensor is at sufficiently high temperature to indicate externally specified lean/rich changes. It is then possible to switch to closed-loop control in the vehicle.

Types

Two-point λ sensors come in different types. The sensor elements can be shaped in the form of a finger with a separate heater element or as a planar element with an integrated heater element which is manufactured using film technology (Figure 3).

Wide-band λ sensor

Design and function

With the two-point λ sensor the oxygen partial pressure of stoichiometric air/fuel mixtures can be measured very accurately in the steep part of the characteristic curve. However, where there is excess air ($\lambda > 1$) or excess fuel ($\lambda < 1$), the characteristic curve is very flat (Figure 2).

The large measurement range of wide-band λ sensors ($0.6 < \lambda < \infty$) enables them to be used in systems with direct injection and stratified-charge operation and in diesel engines. A continuous control concept that can be achieved with a wide-band λ sensor delivers significant system advantages, such as for example controlled component protection. The high signal dynamic response of wide-band λ sensors ($t_{63} < 100$ ms) improves exhaust emissions to the point of low-emission vehicles, which necessarily calls for measures such as individual-cylinder closed-loop control.

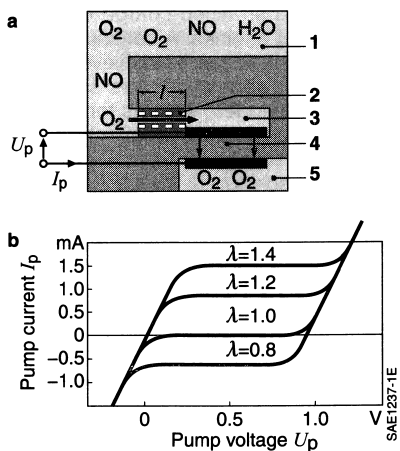
Design and operating principle

The Nernst principle is reversed to wide the measurement range. When a voltage greater than the Nernst voltage is applied to the measuring cell, oxygen is transported as oxygen ions through the pump-cell ceramic to the internal pump and discharged there as free, molecular oxygen into the reference-air chamber. The resulting pump voltage is obtained from the difference between pump voltage (U_p) and the developing Nernst voltage.

The inflow of oxygen molecules is limited in order to establish a linear connection with the externally applied oxygen concentration. To this end the admission of exhaust-gas is limited by a porous, ceramic structure with specifically set pore radii, the so-called diffusion barrier.

Figure 5: Once-cell λ sensor in lean exhaust gas

- a) Cross-section,
b) Characteristic curves.
 l Length of diffusion barrier.
1 Lean exhaust gas,
2 Diffusion barrier,
3 Cavity,
4 Pump cell,
5 Reference air.
The arrows in the pump cell indicate the pumping direction.



The pump current I_P that flows at sufficient pump voltage is, on account of the law of diffusion, directly proportional to the partial pressure in the exhaust gas:

$$\frac{I_P}{4F} = I_M = \frac{AD(T)}{RTl} (p_A(O_2) - p_H(O_2)) .$$

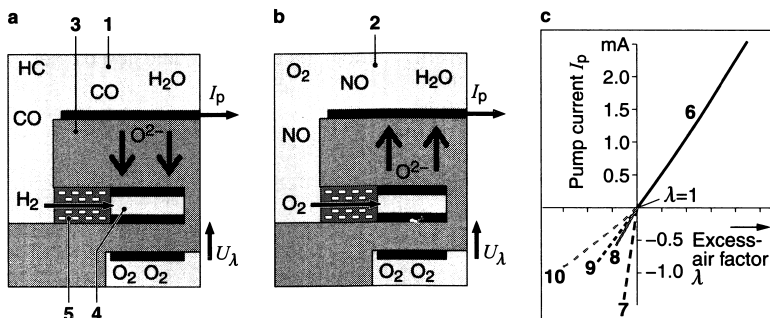
Here $p(O_2)$ is the oxygen partial pressure in the exhaust gas ($p_A(O_2)$) or in the cavity ($p_H(O_2)$), T the temperature, $D(T)$ the temperature-dependent diffusion constant of the diffusion barrier, A its cross-sectional area, and l its length (Figure 5). F is the Faraday constant ($F = 96485.3365 \text{ C/mol}$), R the general gas constant ($R = 8.3144621 \text{ J/mol} \cdot \text{K}$).

If rich exhaust gas is present, the created Nernst voltage of approx. 1,000 mV counteracts the applied pump voltage such that the resulting negative voltage pumps oxygen in the opposite direction into the cavity and thus the linear shape of the characteristic curve is extended into the rich range. The oxygen is obtained for this purpose from the reduction of water and CO_2 on the outer electrode.

The drawback of this simple form of wide-band λ sensor is that the fixed pump voltage must be sufficient in rich exhaust gas to pump oxygen into the cavity and in

Figure 6: Two-cell λ sensor in rich and lean exhaust gas

- a) and b) Cross-section,
c) Sensor characteristic curves.
Depending on the polarity of pump current I_P predominantly reducing exhaust-gas constituents (section a) or oxygen (section b) diffuse through the diffusion barrier.
For $\lambda < 1$ the characteristic curve (section c) is dependent on the exhaust-gas composition, here the characteristic curves of individual exhaust-gas constituents are plotted.
1 Rich exhaust gas, 2 Lean exhaust gas, 3 Pump cell, 4 Nernst cell, 5 Diffusion barrier,
6 Curve for O_2 , 7 Curve for H_2 , 8 Curve for CH_4 ,
9 Curve for CO , 10 Curve for C_3H_8 .



lean exhaust gas to pump oxygen out of it. The internal resistance of the pump cell should therefore be very low. In addition, the measurement range in the rich range is limited by the molecule inflow in the reference passage. An oxygen deficiency in the reference caused by a reference-air contamination or over-range cannot be clearly distinguished. In the case of exhaust-gas exchanges the dynamic response of the one-cell sensor is limited by recharging of the electrode capacities when the pump voltage is changed.

To eliminate these drawbacks, the Nernst cell familiar from the step-change sensor is combined with the oxygen pump cell described above. In the case of rich exhaust gas (Figure 6a), in response to reversing the voltage at the outer pump electrode, oxygen is generated from H_2O and CO_2 , transported inwards through the ceramic, and discharged again in the cavity. There the oxygen reacts with the diffusing, reducing exhaust-gas components. The created inert reaction products H_2O and CO_2 diffused through the diffusion barrier in an outward direction.

The oxygen partial pressure in the cavity is measured by the Nernst cell also connected to the cavity and the pump voltage is corrected by a controller (Figure 7) to a specified reference voltage (e.g. 450 mV). There is then an oxygen partial pressure of 10^{-2} Pa in the cavity.

Because the diffusion limit current increases with the sensor temperature, the temperature must be kept as constant as possible. The highly temperature-dependent resistance of the Nernst cell is measured for this purpose. The operating electronics regulate it by means of the heater element operated with a pulse-width-modulated voltage.

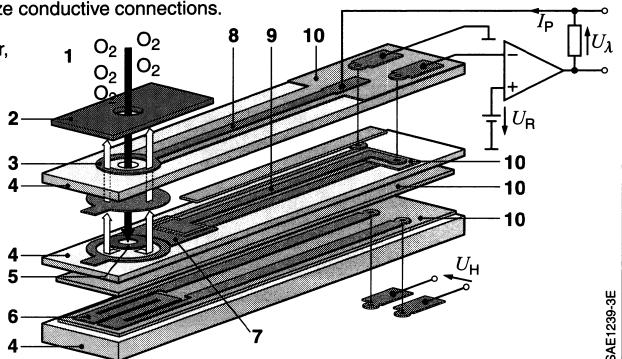
Where the exhaust gas is rich the different diffusion coefficients, which are functions of the masses of the gas molecules, become noticeable through different sensitivities (Figure 6). The signal is therefore used in the ECU for a characteristic curve applied for the relevant gas composition.

The sensor's diffusion limit current and thus the sensitivity are very much dependent on the geometry of the diffusion barrier. It is necessary to adjust the pump current in order to achieve the high accuracy requirement in the manufacturing tolerance. In some sensor types this is done by a hybrid resistor in the sensor plug which acts together with the measuring resistor as current divider. Alternatively, the diffusion limit current can be adjusted already in the sensor-element production process by means of specific openings so that there is no need to make an adjustment at the plug. For subsequent calibration of the sensor in the vehicle the oxygen concentration of the air can be measured in overrun conditions and thus the characteristic curve corrected in the ECU.

Figure 7: Exploded view of a wide-band λ sensor

The vertical lines symbolize conductive connections.

- 1 Exhaust gas,
 - 2 Porous protective layer,
 - 3 Pump cell,
 - 4 ZrO_2 ceramic,
 - 5 Diffusion barrier,
 - 6 Heater element,
 - 7 Nernst cell,
 - 8 Pump electrode,
 - 9 Reference electrode,
 - 10 Al_2O_3 insulation.
- I_p Pump current,
 U_R Reference voltage,
 U_λ Sensor voltage,
 U_H Heating voltage.



NO_x sensor

Application

NO_x sensors are used in the denitrification systems of diesel and gasoline engines. In systems with diesel engines they are installed upstream and downstream of SCR catalytic converters (selective catalytic reduction) and downstream of NO_x storage catalytic converters (NSC, NO_x storage catalysts). In systems with gasoline engines they are used downstream of the NO_x storage catalytic converter.

In these positions the NO_x sensors determine the nitrogen-oxide and oxygen concentrations in the exhaust gas and downstream of SCR catalytic converters also the ammonia concentration as a cumulative signal. In this way the engine-management system receives the current residual concentration of nitrogen oxides, provides for exact metering, and detects any faults in the exhaust system.

Nitrogen oxides are stored as nitrates in NO_x storage catalytic converters. In short rich phases the catalytic converter is regenerated, whereby the nitrates are reduced with the aid of carbon monoxide and hydrogen to nitrogen.

Design and operating principle

The NO_x sensor in Figure 8 is a planar three-cell limit-current sensor. A Nernst concentration cell and two modified oxygen pump cells (oxygen pump cell and NO_x cell), as are already familiar from wide-band λ sensors, form the overall sensor system.

The sensor element consists of several oxygen-conducting, ceramic solid-electrolyte layers insulated against each other, on which six electrodes are mounted. The sensor is fitted with an integrated heater element which heats the ceramic to an operating temperature of 600 °C to 800 °C.

The outer pump electrode exposed to the exhaust gas and the inner pump electrode in the first cavity, which is separated from the exhaust gas by a diffusion barrier, form the oxygen pump cell.

Figure 9: Characteristic curve of the nitrogen-oxide signal

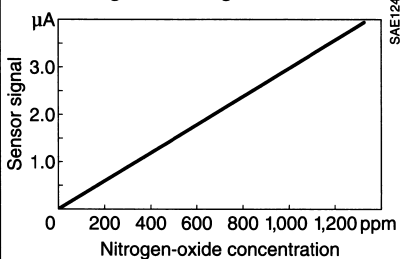
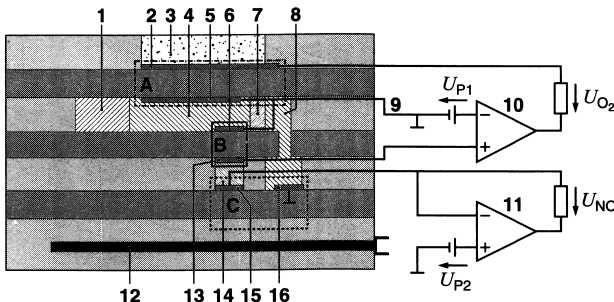


Figure 8: Cross-section of a NO_x sensor

A Oxygen pump cell, B Nernst cell, C NO_x cell.

- 1 Diffusion barrier 1, 2 Outer pump electrode, 3 Porous aluminum-oxide layer,
- 4 First cavity, 5 Inner pump electrode, 6 Nernst electrode, 7 Diffusion barrier 2,
- 8 Second cavity, 9 Common return conductor, 10 Oxygen regulator with voltage transformer,
- 11 NO current amplifier and voltage transformer, 12 Heater element, 13 Reference electrode,
- 14 Reference-gas chamber, 15 NO_x counter-electrode, 16 NO_x pump electrode.



The first cavity contains the Nernst electrode, while the reference-gas chamber contains the reference electrode. Together they form the Nernst cell. These are the functional components which are identical to those of wide-band λ sensors.

In addition, there is a third cell – the NO_x pump electrode and its counter-electrode. The former is situated in a second cavity, which is separated from the first by a further diffusion barrier, the latter is located in the reference-gas chamber. All the electrodes in the first and second cavities have a common return conductor.

The inner pump electrode is, unlike the inner pump electrode in wide-band λ sensors, greatly limited in its catalytic activity by the alloying of platinum with gold. The applied pump voltage U_{P1} is only enough to split (dissociate) oxygen molecules. NO is only minimally dissociated at the adjusted pump voltage and passes the first cavity with low losses. NO_2 as a strong oxidizing agent is converted on the inner pump electrode directly into NO. Ammonia reacts to this in the presence of oxygen and at temperatures of 650°C into NO and water.

Because of the higher voltage at the NO pump electrode and its catalytically improved activity due to the admixture of rhodium, NO is completely dissociated at this electrode and the oxygen is pumped away through the solid electrolyte.

Electronics

In contrast to the other ceramic exhaust-gas sensors, the NO_x sensor is equipped with evaluation electronics (SCU, sensor control unit). It delivers via CAN bus the oxygen signal, the NO_x signal, and in each case the status of these signals.

Incorporated in the evaluation electronics are a microcontroller, an ASIC (Application-Specific Integrated Circuit) for operating the oxygen pump cell, and a high-precision instrument amplifier for the very small NO signal currents.

Characteristic curves

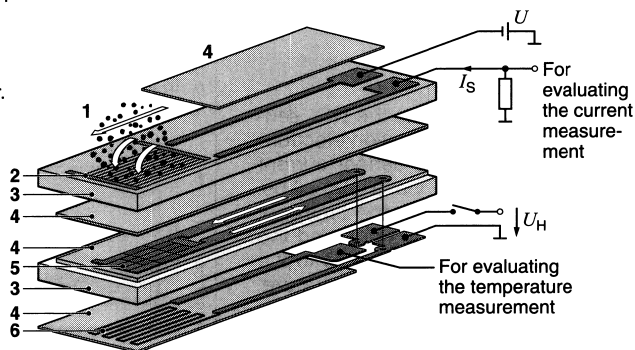
The oxygen signal is 3.7 mA for air. The oxygen characteristic curve is identical to that familiar from wide-band λ sensors (Figure 6c). The NO_x characteristic curve is shown in Figure 9.

Particulate sensor

The emission regulations in the USA and in Europe necessitate the use of diesel particulate filters (DPF) in diesel vehicles. Particulate sensors in addition to the differential pressure sensor are required to comply with future on-board diagnosis legislation (OBD), which places more stringent demands on the monitoring of the functional capability of these particulate filters. The particulate sensors measure the soot emissions downstream of the particulate filter.

Figure 10: Exploded view of the particulate sensor

- 1 Exhaust gas,
 - 2 Interdigital structure with two comb-shaped electrodes,
 - 3 Ceramic,
 - 4 Insulation,
 - 5 Heater element,
 - 6 Platinum meander.
- U Direct voltage, e.g. 60 V,
 I_S Sensor current,
 U_H Heating voltage.



Design

The sensor element consists of an interdigital structure with two comb-shaped platinum electrodes on a ceramic substrate with an integrated heater element, as is familiar from the λ sensor (Figure 10). A platinum meander serves to measure the temperature of the sensor element.

Operating principle

The particulate sensor is a resistive sensor. A direct voltage of for example 60 V is applied at the interdigital structure with initially very high electrical resistance. As a result of the field forces soot particles from the exhaust gas collect on the interdigital electrodes and form increasingly conductive soot paths between the two comb-shaped structures. This produces a monotonously increasing current between the electrodes (Figure 11). A predefined current threshold value is reached after a certain collection time. This triggers regeneration, in which the initial state is re-established when the sensor element is heated and the soot is burned off at temperatures above 600°C.

The time between the start of measurement and the start of regeneration is defined as the trigger time. An integrated temperature-measurement meander is used to control the temperature to ensure that a controlled regeneration of the sensor element takes place.

The particulate-sensor element is, like that of the λ sensor, installed in a sensor housing. Because particulate deposits on the sensor element are desired here, particular emphasis is placed on the design of the protective tube.

Electronics

The particulate sensor, like the NO_x sensor, is equipped with evaluation electronics. The latter supply the sensor current and the signal status via a CAN bus. A microcontroller controls the timing of measurement and regeneration and the compensation of data in response to the measured sensor-element temperature. The electronics also include a voltage stabilizer, a CAN driver, and the output stage for the heater element.

Hydrogen sensors

The use of fuel cells in motor vehicles necessitates the incorporation of hydrogen sensors. This sensor system has two functions – safety monitoring with leak detection (measurement range 0 to 4% hydrogen content in air) and process control with adjustment of operating conditions (measurement range 0 to 100%).

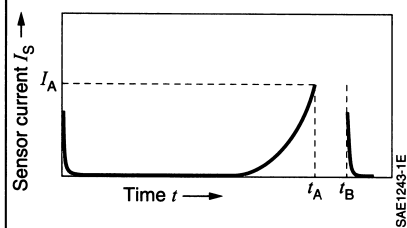
The most common measurement principles are described in descending frequency of use. For the most part different methods are combined to reduce cross-sensitivity to other gases or to increase sensitivity and widen the measurement range [3].

Electrochemical measurement principle

In the case of amperometric measurement a constant voltage is applied to an electrolyte that conducts only protons (e.g. sulfonated tetrafluoroethylene polymer). The electrolyte is covered by a diffusion barrier which is very selective in admitting only hydrogen. These sensors thus have long-term stability. At the electrode hydrogen splits into protons, which flow as pump current through the electrolyte. The electrons flow through the electrodes, driven by the applied voltage, via the outer electric circuit to the other side of the electrolyte. Here they recombine with oxygen on the electrode to form water. The current intensity is according to Faraday's law proportional to the number of protons, which in turn is determined by the diffusion by the diffusion barrier (see λ sensor).

Figure 11: Current curve between the electrodes of a particulate sensor

I_A Trigger threshold,
 t_A Trigger point for regeneration,
 t_B Start of next measurement cycle.



Potentiometric measurement methods utilize the potential difference between two electrodes. One electrode with a platinum or palladium catalyst is situated in the hydrogen environment, the other electrode is situated for example in air. According to the Nernst equation a potential difference develops (see Fuel cell). The potentiometric sensors are cross-sensitive to carbon monoxide that covers the catalyst. The age quickly and have a high drift. The measurement range is between 100 ppm and 100%.

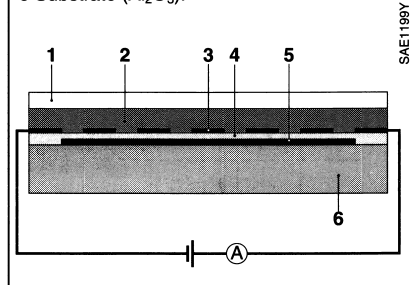
Resistance-based measurement principle

Palladium and semiconductor metal oxides (e.g. SnO_2) exhibit a change in resistance after the adsorption of hydrogen. The semiconductor metal-oxide sensor (Figure 12) consists of a gas-filtering diaphragm which should only admit hydrogen. The sensitive layer absorbs the hydrogen and induces the change in resistance, which is measured by a Wheatstone bridge.

A MOSFET (see Field-effect transistor) can also be used with a palladium gate as a variant. This alters the current between source and drain proportionally to the hydrogen absorbed at the gate. In a Schottky-diode arrangement (see Schottky diode) the breakdown voltage decreases when hydrogen is adsorbed.

Figure 12: Resistance-based measurement principle of a hydrogen sensor

- 1 Gas-filtering diaphragm,
- 2 Sensitive layer,
- 3 Semiconductor metal-oxide film,
- 4 Insulating layer,
- 5 Heater,
- 6 Substrate (Al_2O_3).



The measurement range for the resistance-based measurement principles is between 10 ppm and 2%.

Catalytic measurement principle

Heat is generated when adsorbed gases oxidize on the surface of a catalyst. In a pellistor a wire consisting of catalyst material (e.g. platinum or palladium) exposed to the hydrogen is heated and as a result undergoes a change in resistance dependent on the hydrogen concentration, while the temperature and resistance of a reference wire remain unchanged. The resistors are integral parts of a Wheatstone-bridge circuit, with which the change in resistance is measured and from this the hydrogen concentration is inferred.

In the thermoelectric method the voltage build-up due to the temperature difference (Seebeck effect) is utilized.

The catalytic methods are cross-sensitive to other oxidizable gases and require a minimum quantity of oxygen (5 to 10%) as the oxidation partner; the measurement range therefore is between 1% and 90 to 95% hydrogen concentration.

References for gas and concentration sensors

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- [2] T. Baunach, K. Schänzlin, L. Diehl. Sauberes Abgas durch Keramiksensoren. Physik Journal 5 (2006) No. 5.
- [3] T. Hübert et al.: Hydrogen sensors – A review, Sensors and Actuators B 157 (2011) 329 – 352.

Optoelectronic sensors

Internal photoelectric effect

The internal photoelectric effect forms the basis of optoelectronic sensor elements. Light can be seen as a stream of individual light quanta (photons). The energy E_{Ph} of a photon is only dependent on its frequency f or its wavelength λ :

$$(1) E_{Ph} = hf = \frac{hc}{\lambda}$$

where

h Planck's action quantum,

c Speed of light.

When photons strike atoms, they can each release an electron from the outer electron shell if the energy is sufficient. The energy required for release corresponds to the difference between the energy level E_V of the valence band of the atom and the level E_L of the conduction band, i.e. the band gap E_g .

$$(2) E_g = E_L - E_V.$$

To release an electron, the photon energy E_{Ph} must therefore be greater than the band gap E_g . In a pure semiconductor, charge-carrier pairs (electrons and holes) are created by the absorption of photons. The band gap to be overcome of, for example, silicon is $E_g = 1.12$ eV at room temperature. Without special measures the charge-carrier pairs created recombine already after a short time. However, the radiation created in the process is not in the visible range in the case of silicon.

In highly doped semiconductors, the above-mentioned intrinsic photoelectric effect is supplemented by the extrinsic photoelectric effect. Because the energy gap to be overcome is significantly lower in such extrinsic sensors, they are also suitable for radiating a larger wavelength (infrared range).

No further release occurs for energies $E_{Ph} < E_g$. According to equation (1), this corresponds in the case of silicon to a limit wavelength of $\lambda_g = 1.1 \mu\text{m}$ (near infrared). Light with larger wavelengths or lower frequency is not longer absorbed; silicon becomes transparent here.

Light-sensitive sensor elements

Photoresistors

Incident light causes charge-carrier pairs to be created in a sensor configured as a resistor (LDR, light-dependent resistor); these charge-carrier pairs increase the conductance G . They recombine after a short time (milliseconds range); but nevertheless the charge-carrier concentration increases in stationary equilibrium with the illuminance E according to the following law:

$$(3) G = \text{const} \cdot E^\gamma \quad \text{where } \gamma = 0.7 \text{ to } 1.$$

The light-sensitive materials usually used are cadmium sulfide CdS ($E_g = 1.8$ eV; $\lambda_g = 0.7 \mu\text{m}$) and cadmium selenide CdSe ($E_g = 1.5$ eV; $\lambda_g = 0.8 \mu\text{m}$) on ceramic substrates.

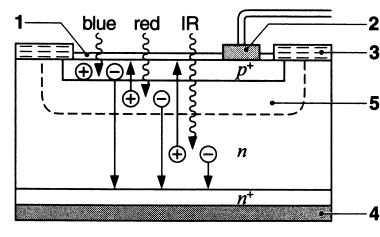
Semiconductor pn junctions

There is essentially no difference between a photocell, a photodiode, and a phototransistor. They all use the photocurrent or no-load voltage in illuminated pn semiconductor contacts as the measuring effect. The elements differ, however, in the way they operate.

Charge carriers which are created by the internal photoeffect in the depletion layer of a pn semiconductor contact (Figure 1) are immediately accelerated by the electric field in the space-charge region with low charge-carrier concen-

Figure 1: Separation of created electron-hole pairs in a planar semiconductor component with pn junction

- 1 Optical coating,
- 2 Contact,
- 3 SiO_2 ,
- 4 Metal contact,
- 5 Space-charge region.



tration, as a result of which the charge carriers are immediately split after they have been created (drift current). Their recombination is practically prevented and photosensitivity is significantly increased.

Photocells

Photocells are operated without external bias and can be operated both at no load (photovoltaic effect) and in a short-circuit. They have accordingly a low background noise and thus a high detection capability.

The characteristic curves applicable to these operating modes (Figure 2) can be easily derived as special cases from a diode polarized in the forward direction with the voltage U with the thermally conditioned off-state saturation current I_S and the photocurrent I_{ph} also flowing in reverse direction:

$$(4) \quad I = I_S e^{\frac{eU}{kT}} - I_{ph}$$

where
 e Elementary charge,
 k Boltzmann's constant,
 T Absolute temperature.

Special cases:

$$(5) \quad U = 0 \text{ (short-circuit)} \\ \rightarrow I = I_K = -I_{ph};$$

$$(6) \quad I = 0 \text{ (no load):}$$

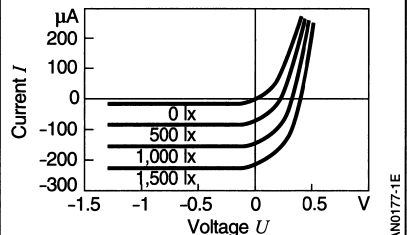
$$\rightarrow U = U_L = \frac{kT}{e} \cdot \ln \left(\frac{I_{ph}}{I_S} + 1 \right).$$

Photocells are usually configured with a very large irradiation-sensitive surface, and provide accordingly relatively high photovoltaic current also (e.g. $I_{ph} = 250 \mu A$ at $E = 1,000 \text{ lx}$). Their time constant is proportionally high and is typically approximately 20 ms.

Photodiodes and phototransistors

Photodiodes are operated with constant bias U_S in the reverse direction, where the photocurrent flowing as reverse current is linearly dependent on the illuminance E (Figure 3). The space-charge region is increased in size by the applied

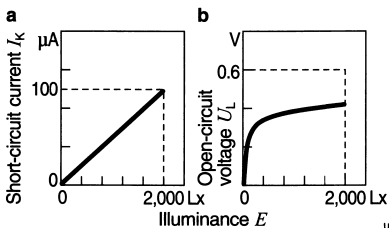
Figure 3: Characteristic curves for a photodiode for constant illuminance E



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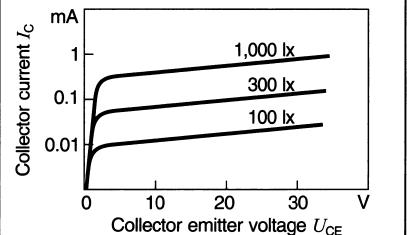
Figure 2: Characteristic curves for a photocell as a function of illuminance E

- a) Short-circuit current I_K ,
b) Open-circuit voltage U_L .



U4N0176-1E

Figure 4: Characteristic curves for a phototransistor for constant illuminance E



U4N0178E

reverse voltage. This reduces the junction capacitance in such a way that the cutoff frequency of such a photodiode is typically a few MHz.

In the case of the phototransistor shown in Figure 4 (*nnp* type), the collector-base diode polarized in the reverse direction acts as a photodiode. In this way, the collector, like every transistor, supplies a photocurrent higher by the current-amplification factor B (≈ 100 to 500) (corresponding to base current). However, the higher sensitivity comes at the expense of a slightly worse frequency dynamic and a slightly worse thermal characteristic.

Application

Dirt sensor

The sensor measures the level of contamination on the headlamp lens to furnish the data required for automatic lens cleaning systems.

The sensor's photoelectric reflected-light barrier consists of a light source (LED) and a light receiver (phototransistor). The source is positioned on the inside of the lens, within the cleansed area (Figure 5), but not directly in the headlamp beam path. When the lens is clean, or covered with rain droplets, the

infrared measurement beam emitted by the unit passes through the lens without being obstructed. Only a minuscule part is reflected back to the light receiver. However, if it encounters dirt particles on the outer surface of the lens, it is reflected back to the receiver at an intensity that is proportional to the degree of contamination and automatically activates the headlamp washer unit once a defined level is reached.

Rain sensor

The rain sensor recognizes rain droplets on the windshield, so that the windshield wipers can be triggered automatically. The driver, however, can still use the manual controls.

The sensor consists of an optical transmission and reception path (similar to the dirt sensor). However, the light is directed toward the windshield at an angle. A dry outer surface reflects all the light (total reflection) back to the receiver which is also mounted at an angle (Figure 6). When water droplets are present on the outer surface, a substantial amount of the light is refracted outward, thus weakening the return signal. The windshield wiper also responds to dirt once the activation threshold is exceeded.

Figure 5: Dirt sensor for headlamp lens

- 1 Lens,
- 2 Dirt particle,
- 3 Sensor element,
- 4 Transmitter,
- 5 Receiver.

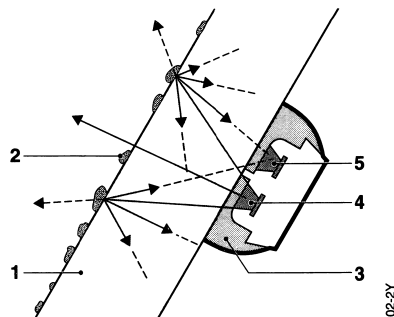
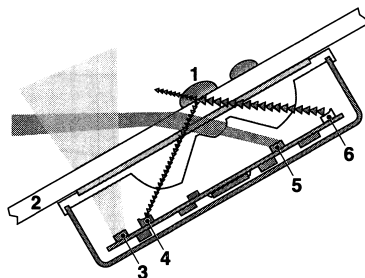


Figure 6: Rain sensor for windshields

- 1 Raindrop,
- 2 Windshield,
- 3 Ambient-light sensor,
- 4 Photodiode,
- 5 Light sensor aligned to far distance,
- 6 LED.



Ultrasonic sensor

Application

Today's parking-aid and maneuvering systems (see Parking-aid systems) use ultrasound-technology ultra-short-range sensors with a detection range of up to 5.5 m. They are integrated in the bumpers of motor vehicles and serve to calculate distances to obstacles and to monitor the vehicle's surroundings when parking and maneuvering. Sound or even visual alerts are issued to the driver as the vehicle approaches an obstacle.

These sensors also permit the use of a parking assistant, which either issues instructions to the driver for optimum parking or steers the vehicle into the parking space while the driver only needs to take care of longitudinal guidance of the vehicle.

Ultrasonic-sensor design

Figure 1 shows by way of example a fourth-generation ultrasonic sensor. It is comprised of a plastic case with integrated plug-in connection, an ultrasonic transducer (aluminum pot with diaphragm onto the inside of which has been glued a piezoceramic element), and a printed-cir-

cuit board with transmit and evaluation electronics. They are electrically connected to the control unit by three wires, two of which supply the power. The third, bidirectional wire is responsible for activating the transmit function and returning the evaluated received signal to the ECU.

In the meantime sixth-generation sensors have been introduced into the systems by Bosch. They are characterized by digital signal processing, which prevents the systems of different vehicles from influencing each other, and by a further-extended sensing distance of up to 5.5 m, blindness detection (in the event of icing or fouling), and improved short-range detection.

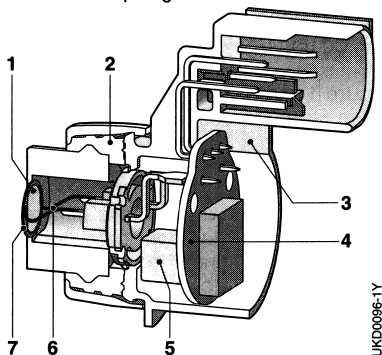
Ultrasonic-sensor operating principle

The ultrasonic sensor receives a digital transmit pulse from the ECU. The electronic circuit then induces the aluminum diaphragm to oscillate with square-wave pulses of approximately 300 μ s duration at resonant frequency (around 48 kHz) with the result that ultrasonic pulses are emitted. No reception is possible during the relaxation time of approximately 900 μ s. The diaphragm, which has meanwhile returned to rest, is made to vibrate again by the sound reflected back from an obstacle. These renewed oscillations are outputted by the piezoceramic element as analog electrical signals and amplified and converted into a digital signal by the sensor electronics.

Ultrasonic sensors usually have for the described application a selective emission characteristic (see Parking and maneuvering systems) with a wide horizontal sensing range (for sensing as many objects as possible) and a narrow vertical sensing range (for avoiding earth reflections).

Figure 1: Cutaway view of an ultrasonic sensor

- 1 Piezoceramic element,
- 2 Decoupling ring,
- 3 Plastic case with plug connector,
- 4 Printed-circuit board with transmit and evaluation electronics,
- 5 Transformer,
- 6 Bond wire,
- 7 Aluminum diaphragm.



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Radar sensors

Application

Radar technology has since 1999 been used with increasing regularity in motor vehicles and supports drivers in their driving tasks. The radar sensor detects objects in front of the driver's vehicle (e.g. other vehicles, pedestrians, roadside structures) and measures their distances, relative speeds and transverse offset to the driver's vehicle. The ACC system (ACC, Adaptive Cruise Control) uses these measurements, adapts the vehicle's driving speed to the traffic in front, and thereby relieves the driver in their driving tasks (see Adaptive cruise control).

Thanks to its excellent properties in terms of fast and precise measurement of distance, relative speed and transverse offset, the radar sensor is particularly well suited for use in active and passive safety functions. Further examples of where radar technology is used are predictive emergency braking systems (PEBS) and pre-crash detection.

Radar principle

The electromagnetic waves emitted by the radar device are rebounded against metal surfaces or other reflecting materials and are picked up again by the radar's receiving section. The distance to the objects in the sensing range can be measured from the propagation times of these waves. The Doppler shift of the reflected electromagnetic waves enables the relative speed of all the detected objects to be measured directly. The transverse offset is determined with an angle estimation which is based on the evaluation of numerous emitted radar beams.

Test methods

The signals received are compared in time or frequency with the transmitted signals. The methods used differ considerably particularly in the way in which the signals are compared. The transmitted waves are modulated to enable a received signal to be uniquely assigned to a transmitted signal. The most common modulations are pulse modulation in which 0.5 to 30 ns pulses are generated, corresponding to a wavelength of 0.15 to 10 m, and frequency modulation in which, during transmission, the instantaneous frequency of the waves is varied over time.

For all radar methods, the distance measurement is based on the direct or indirect propagation-time measurement between when the radar signal is transmitted and when the echo signal is received.

Pulse modulation

In the case of a pulse-modulated signal, the propagation time τ (time difference) between transmitted pulse and received pulse is measured. The received wave packet must be demodulated in order to extract the required information. Using the speed of light, the distance to the vehicle traveling in front can be calculated from this time differential. With direct reflection, this is defined by twice the distance d to the reflector divided by the speed of light c :

$$\tau = \frac{2d}{c}.$$

For a distance of $d = 150$ m and $c \approx 300,000$ km/s, the propagation time $\tau \approx 1.0$ μ s.

Figure 1 shows the block diagram for a pulse radar. An oscillator which oscillates at a frequency of for example 24 GHz transmits its signals to a power splitter. Its outputs are fed to two high-speed switches in the two channels pictured in the diagram. In the upper path (transmitting path) the signals from a pulse generator are first modulated, in which the

square-wave pulses are converted into a suitable shape to activate and transmit the carrier signal. The modulated signal is then output to the high-speed switch (high-frequency modulation switch). The signals pass from this assembly to the transmitting antenna.

In the lower parallel path (receiving path), to determine the propagation time, a variable delay generates reference signals which feed to a high-speed switch in the receiving path. The received echo signal is coherently mixed with the output signal from the oscillator in order to identify frequency changes in the received echo signal. Coherence in this context means that the phase of the transmitted pulse remains is retained in the reference signal. This procedure presupposes a phase-stable oscillator. The frequency change is determined by the Doppler filter and determines the relative speed.

A radiated peak power of 20 dBm EIRP (power level with the reference quantity 1 mW, Equivalent Isotropic Radiated Power) produces a measurement distance of 20 to 50 m, depending on the size and reflection properties of the object in question and the sensitivity of the receiving path. The minimum measurement distance is typically 0.25 cm.

FMCW modulation

Figure 2 shows the block diagram for an FMCW radar (Frequency Modulated Continuous Wave). A 77 GHz VCO (voltage-

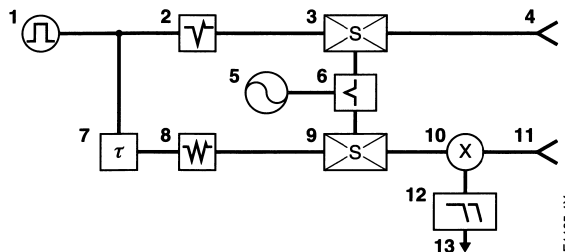
controlled oscillator) supplies the transmitting antenna. The receiving antenna transmits the signal reflected by the object to the reception mixers, which mix the received signal with the current transmitted signal of the VCO and thus transform to low frequencies in the range 0 to 500 kHz. The signals are amplified, digitized, and to determine the frequencies subjected to a high-speed Fourier analysis effected in software (see Fourier transform).

The operating principle of frequency generation is explained in the following. The frequency of the 77 GHz VCO is compared continually by PLL closed-loop control (phase-locked loop) with a stable quartz-based reference oscillator and regulated to a prespecified setpoint value. The PLL is altered during a measurement in such a way that for the transmit frequency f_s a linearly rising frequency ramp is created over time – followed by a linearly falling frequency ramp (Figure 3). The mean transmit frequency is f_0 . The signal reflected and received from a vehicle driving in front f_E is delayed according to the propagation time, i.e. it has in the rising ramp a lower frequency and in the falling ramp a frequency f_E higher by the same amount Δf_{FMCW} . The frequency difference Δf_{FMCW} is a direct measure of the distance d , dependent on the gradient s of the ramp:

$$\Delta f_{\text{FMCW}} = |f_s - f_E| = \frac{2s}{c} \cdot d.$$

Figure 1: Block diagram of pulse radar

- 1 Pulse generator,
- 2 Modulator for pulse shaping,
- 3 High-speed switch,
- 4 Transmitting antenna,
- 5 24 GHz oscillator,
- 6 Power splitter,
- 7 Variable time delay,
- 8 Modulator for pulse shaping,
- 9 High-speed switch,
- 10 Mixer,
- 11 Receiving antenna,
- 12 Doppler filter,
- 13 Output.



If there is additionally a relative speed Δv to the vehicle traveling in front, the receive frequency f_E is, on account of the Doppler effect, increased (when approaching) or decreased (when the distance increases) in both the rising and falling ramps by a specific, proportional amount Δf_D :

$$\Delta f_D = \frac{2f_0}{c} \cdot \Delta v \quad (\text{approximation for } v \ll c).$$

In other words, there are two different difference frequencies Δf_1 and Δf_2 . For the rising ramp:

$$\begin{aligned} |\Delta f_1| &= |f_S - f_E| = \Delta f_{\text{FMCW}} - \Delta f_D \\ &= \frac{2}{c} \cdot (s d - f_0 \Delta v). \end{aligned}$$

For the falling ramp:

$$\begin{aligned} |\Delta f_2| &= |f_S - f_E| = \Delta f_{\text{FMCW}} + \Delta f_D \\ &= \frac{2}{c} \cdot (s d + f_0 \Delta v). \end{aligned}$$

Their addition produces the distance d , and their subtraction the relative speed Δv of the objects:

$$d = \frac{c}{4s} \cdot (\Delta f_2 + \Delta f_1),$$

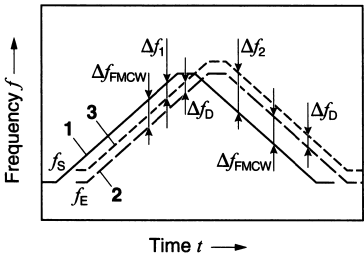
$$\Delta v = \frac{c}{4f_0} \cdot (\Delta f_2 - \Delta f_1).$$

Antenna system and determining the angle

The antenna system has not only to transmit and receive the high-frequency signals, but also to estimate the transverse offset of the objects. This is required

Figure 3: Distance and speed measurement with a linear FMCW radar

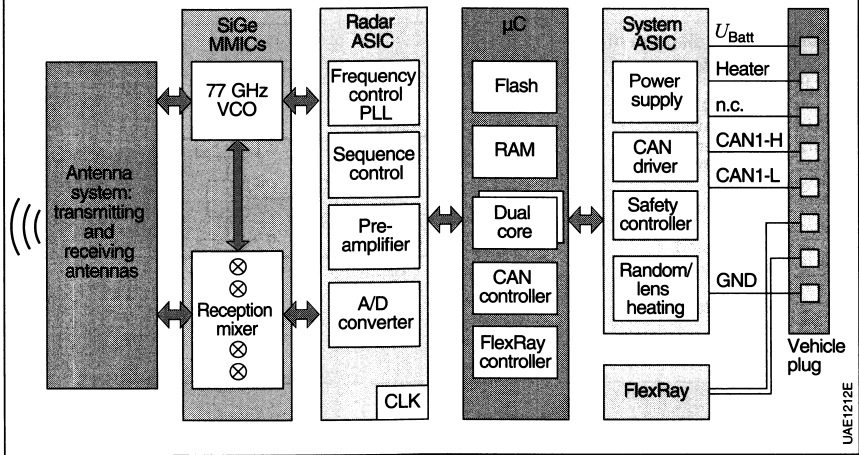
- 1 Transmit frequency f_S ,
- 2 Receive frequency f_E without relative speed,
- 3 Receive frequency f_E with relative speed.
- Δf_{FMCW} Frequency difference between transmitted and received radar signals,
- Δf_1 Frequency difference on the rising ramp with relative speed,
- Δf_2 Frequency difference on the falling ramp with relative speed,
- Δf_D Change of receive frequency with relative speed.



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Figure 2: Block diagram of a 4-channel FMCW radar

SiGe MMIC: mm-wave-IC, integrated circuit (silicon-germanium technology).



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to assign the objects to lanes. Radar systems determine the relative position by estimating the angle under which the receiving antenna locates an object. At least two, or better still more than two receiving antennas are required for this purpose. This can be done by directing a single radar beam (scanning) and also by several parallel, overlapping radar beams.

The gains of the complex amplitudes (phases and amounts) which are measured for an object in neighboring beams allow a conclusion to be drawn about the relative reception angle to the radar-sensor axis. In practice four radar beams are frequently used, achieving an angle accuracy of up to 0.1° and an angle separation of up to 4° .

There are many ways of technically realizing the antenna system. The two most common variants are the lens-antenna system and the patch-array-antenna system.

Lens-antenna system

The lens-antenna system consists of a number of single patches (typically a metallic rectangle seated on a p.c.b. suitable for high frequencies) which are arranged in the focal plane of a dielectric plastic lens. The lens concentrates the radar beams of the single patches horizontally and vertically, thereby increasing the range of the radar sensor. The lateral offset of the single patches creates an angle offset of the radar beams and thus fan-shaped transmit and receive characteristics, which are used to determine the positioning field and to determine the angle.

The lens-antenna system is usually a monostatic system, i.e. the transmitting patches also serve as the receiving patches such that directional couplers are used in the reception mixers to separate the received signals from the transmitted signals.

Patch-array-antenna system

The patch-array-antenna system, in contrast to the lens-antenna system, as a rule has a bistatic design. The transmitting antenna in this system consists of a large number of single patches arranged in rows and columns which are wired in such a way that superposition produces a concentrated radar beam along similar lines to concentration by a lens.

The receiving antenna typically consists of a number of single patches arranged in columns which are electrically separated from each other and arranged next to each other. The offset of the individual reception columns generates a phase shift between the received signals of a detected object which is used to determine the angle. A reception column can in an individual case also consist of a number of wired columns.

Variants of radar sensors

In the past a distinction was made between short-range radars (SRR, usually in the 24 GHz frequency band) and long-range radars (LRR, in the 76 GHz frequency band). In the meantime the applications are merging and sensors are increasingly covering both ranges such that mid-range radars (MRR, in the 76 to 81 GHz Band) will dominate the market, supplemented by a long-range radar. Short-range radars have a typical range of 20 to 50 m and a beam angle of up to 160° . Long-range radars have ranges of 250 m and beam angles of up to 30° ; mid-range radars have ranges and beam angles in between.

Vehicles in the future will have up to five radar sensors all round the outer skin, placing a virtually continuous envelope around the vehicle and providing the opportunity for further assistance functions to make driving safer and more comfortable.

Lidar sensors

Applications

Lidar sensors (Light Detection and Ranging) have been used for adaptive cruise control applications (ACC) in Japan and occasionally in the USA since around 2000. Since 2008 the multi-beam lidar has opened up the volume segment for automatic emergency-braking functions. By 2020 a rapidly increasing number of lidar sensors for highly automated driving functions is expected, driven by the need for a redundant sensor configuration with different physical measurement principles where possible.

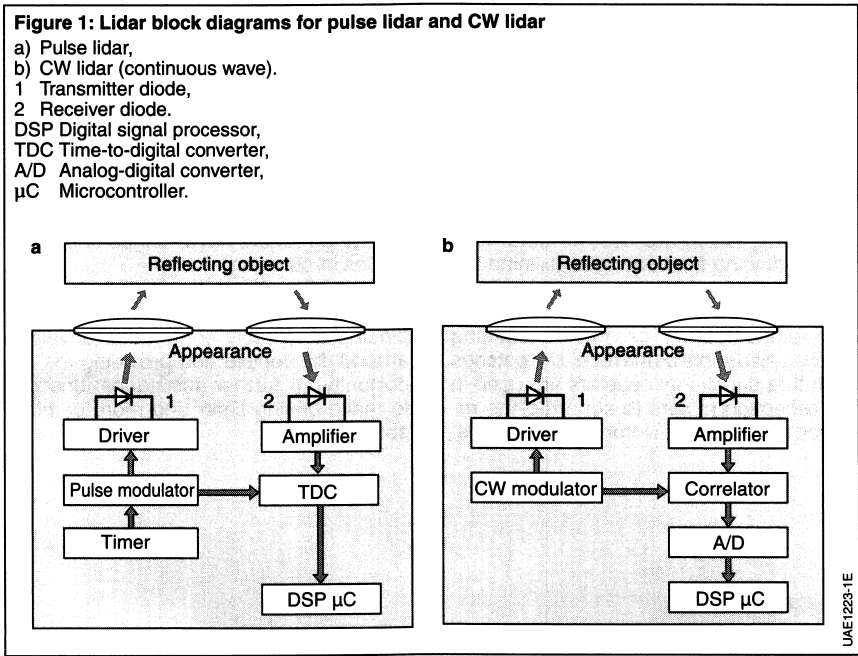
Measurement principle

Today's lidar sensors typically achieve ranges of 150 to 250 m with a distance accuracy of 5 to 15 cm. The angle resolution is typically 0.25 to 1°. The measurement rate is for the most part between 10 and 25 Hz. Simple, non-scanning lidar sensors with one or a few fixed beams supply individual measuring points of the

surrounding area (distance and intensity). Complex lidar sensors have a number of beams which can be specifically deflected to scan the surrounding area. Such high-resolution lidar sensors achieve several thousand measuring points per measuring cycle. With the available intensity information the measured data are comparable with video images.

Unlike most radar sensors, a lidar sensor does not measure the object speed directly. Instead, it is calculated by differentiating the distance signal, which results in a certain delay and reduced signal quality. On the other hand, the good lateral resolution of a scanning lidar is far superior to the typical radar sensors used today.

Lidar sensors operate in the close infrared range between 800 and 1,000 nm, or to increase eye safety around 1,550 nm. Lidar beams can occasionally be significantly damped by fog and conditions of poor visibility, in particular spray. This can reduce the measurement range accordingly. They are therefore less well suited than radar sensors for safety applications.



Infrared radiation is modulated in its intensity, not in its frequency. The block diagram for a lidar sensor is shown in Figure 1. A lidar sensor emits modulated infrared radiation, which is reflected by an object and received by one or more photodiodes in the sensor. Forms of modulation can be: square waves, sinusoidal oscillations or pulses. The modulator transmits the modulation information to the receiver. In this way, the received signal can be compared with the transmitted signal in order to determine either the phase difference of the signals or their propagation time, and from this to calculate the distance to the object.

The signal-to-noise ratio is very much dependent on the type of modulation, the best results being achieved with pulse modulation. Pulse modulation is therefore the method used in practice for lidar sensors with long ranges.

There are currently three fundamental principles for measuring light propagation time:

Direct pulse-propagation-time method

With the direct pulse-propagation-time method a very strong, short pulse of light (typically up to 75 W pulse height, 2 to 10 ns pulse duration, pulse repetition rate up to 150 kHz) is emitted. In the received light the pulse reflected by the object is detected using different methods (e.g. scanning and correlation analysis or edge detection by threshold-value comparison) with regard to chronological position and signal shape (time-to-digital converter, TDC). The distance is calculated from the chronological position relative to the emitted pulse via the speed of light. The reflectivity can be inferred from the signal shape. But a classification can also be made as to whether the reflection comes from a hard target (object) or a soft target (atmospheric interference, e.g. fog). Sometimes the signal shape is also used to improve the distance estimation (e.g. walk-error compensation). To adapt to the large dynamic range required, some receiver circuits operate primarily in saturation, with the result that only edge detection is possible. Other methods perform a dynamic gain adjustment, e.g. increasingly with rising propagation time. Newer methods work with statistical methods,

e.g. threshold-value comparisons within the noise of ambient light (during the continuous event measurement).

Lateral and vertical resolution is achieved by a multibeam configuration, by mechanical scanning or by special reception arrays.

Multibeam lidars have a very limited resolution. The use of such lidars is only sensible where rough volume elements are to be checked for the presence of an object (e.g. during an emergency-braking function for areas in front of the vehicle for which only collision mitigation can still be achieved).

Mechanical scanning has the advantage of a very fine angle resolution when only one or a few transmit and receive elements are used. Beam deflection was until recently achieved either by a rotating mirror (prism mirror) or by directing the optical element of the transmitter or receiver. Now solutions are being used more frequently in which transmitter, receiver and optical elements are located on a rotating plate. Energy transmission to the plate is effected via sliding contacts or by non-contacting means.

MEMS micro-mirrors (Micro-Electro-Mechanical Systems) are used as deflectors for miniaturization purposes. This trend could gain acceptance at least for deflecting the transmitted beam.

In a newer form reception arrays (focal-plane arrays, FPA) with up to 256×256 pixels are used in which each pixel performs a distance measurement by scanning the received pulse. On the transmission side either a single, very strong pulse is emitted (flash lidar) or light pulses are deflected by means of a scanning device. The maturity of these technologies is still low today.

In a further special form, range gated viewing or range scanning, a very short (lasting a few nanoseconds) gate window of the receiver is shifted incrementally in time and for each increment merely the intensity of the received light of the gate window is measured. The advantage is simple conversion in the receiver. The disadvantage is that a new laser pulse is required for each distance increment.

Indirect propagation-time methods

With the indirect propagation-time method with phase displacement an amplitude-modulated light signal (in theory for the most part assumed to be sinusoidal, up to a few 10 W CW output) is emitted and correlated with the reflected light in the detector. The light propagation time and thus the distance can be inferred directly from the phase displacement. In order to determine the phase displacement, the signal amplitude, the phase relation, and the signal offset must be determined from the received signal. To determine the three unknown quantities, four measured values are recorded and the solution is ascertained from the overdetermined system. The measured values are recorded in four measurement phases corresponding to the phase displacements 0° , 90° , 180° , and 270° . Over a period of a few milliseconds charge carriers converted from photons are distributed – controlled by the amplitude of the transmission modulation – to two charge zones (charge-carrier swing). After all the partial measurements have been completed the distance to the object can be inferred from the charge conditions. Because of this mixer comparable with the radar in the pixel imagers structured in this way are also called photonic mixing devices (PMD). In order to prevent a saturation of the charge zones for example by strong background light, it is possible to remove equal components in the charge-carrier swing (SBI, suppression of background illumination).

In a form involving very many PMD pixels such lidar sensors are also called range imagers because they combine characteristics of both lidar technology and camera technology. They can be considered to be video sensors which have the additional ability to measure the distance to the nearest object with each camera pixel. If the problems that still exist can be surmounted, PMD technology must be considered a serious alternative to other sensors in the short and medium ranges.

Indirect propagation-time method with high-speed exposure control

With the indirect propagation-time method with high-speed exposure control a long, if possible square-wave pulse of high amplitude is emitted (several 100 ns pulse duration, up to 100 W pulse height). The receive pulse is integrated in the receiver in two exposure sections. The first exposure section corresponds to the transmission duration so that as the distance to the object increases an ever-decreasing proportion of the reflected light still shines into the gate window and consequently can be integrated. If the object distance is above the distance of the corresponding transmission duration (upper distance limit), no more light can be integrated. This first partial measurement is ambiguous with regard to object reflectivity and object distance. Clarity can be achieved with the second exposure section. This corresponds to twice the transmission duration so that the entire reflected pulse is incident and thus contains a clear indication of the entire quantity of light reflected by the object (dimension of the reflectivity for this distance). Both partial measurements contain a further offset as a result of the background light. The background light is therefore determined in a third partial measurement without pulse lighting. This technology, in view of its integrating character, currently functions only in bright ambient light.

There are currently two forms of implementation. In this first variant a high-speed-switching standard camera imager with very high resolution is used to perform the three partial measurements. The distance images are calculated in a downstream stage on a computer. In the second variant the measurement principle is implemented directly on the CMOS imager. However, because of the smaller space factor (space requirement for implementing the measurement principle), only lower resolutions can be achieved.

Video sensors

Application

Images contain the greatest amount of information for human beings. Consequently, the obvious approach within the context of developing driver-assistance systems is to record images, to extract the relevant details from such images, and to identify dangerous situations by means of image-processing methods.

The first stage has already seen the introduction onto the market of video-based functions such as, for example, night-vision systems, lane departure warning, and road-sign recognition. In a second stage, functions which (above all by the interaction of several sensors) intervene in the vehicle dynamics by acting on the brakes, steering and throttle open up new, effective perspectives for the sustained avoidance of accidents and mitigation of the consequences of accidents.

Two different tasks are performed in an automobile system within this context. When the requirement is to generate a particularly high-contrast, brilliant image, as is needed in night-vision systems, image editing is performed. The edited image is then output directly in a display. The second task involves extracting specific image content by using special algorithms (image processing, e.g. road-sign recognition). The information thereby acquired can then be used to issue an alert to the driver in the display or to generate a vehicle intervention by way of actuators.

Basic principles of photosensing

Creation of photoelectric current

When photons shine into a semiconductor, electron-hole pairs are generated. These in turn generate an electric field, recombine and generate a photoelectric current. Here, the quantity "quantum efficiency η " describes how many electron-hole pairs are generated by one photon.

Virtually all the photons which penetrate into the semiconductor are converted into electric charges. There is however a strong spectral dependence of the mean absorption length in which this photoconversion occurs. Short-wave light

is principally absorbed on the surface of the semiconductor, while long-wave light penetrates deep into the semiconductor. Images with a high content of red and infrared wavelength ranges (e.g. systems for night-vision improvement) therefore demonstrate much less contrast than images which are recorded in the short-wave spectral range. It is therefore essential for night-vision display systems to process images in the interests of improved contrast with brilliant images. For consumer applications optical filters are frequently incorporated in front of the camera in order to cut off the infrared content of the spectrum.

The photoelectric current is proportional over many factors of ten (greater than ten) to the incident luminous flux and is linear over a wide dynamic range. This is what makes semiconductor photosensors such an attractive prospect for numerous consumer and measurement applications.

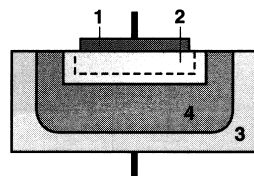
The two most important photosensitive semiconductor structures are the photodiode and the metal-oxide semiconductor capacitor (MOS capacitor), as are used in CCD sensors. Both these semiconductor structures are manufactured with standard semiconductor processes.

Photodiode

The photodiode (Figure 1) consists of a combination of semiconductor materials of differing conductive properties. An electric field exists in the space-charge region at the junction between the two semiconductor materials. At the same time this space-charge region demonstrates a cer-

Figure 1: Photodiode

- 1 Contact,
- 2 n^+ silicon substrate,
- 3 p silicon substrate,
- 4 Space-charge region.



tain capacitance which behaves in inverse proportion to its thickness. Photodiodes typically work by being changed to a certain potential (reset voltage) and then being exposed to light. The photoelectrically generated charges now spread to the entire space-charge region and are stored in the photodiode capacitor. The residual voltage is measured once the photodiode has been exposed to light. The difference between this voltage and the reset voltage is a measure of the quantity of incident light.

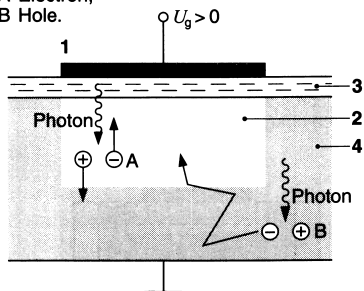
Metal-oxide semiconductor capacitor

The metal-oxide semiconductor capacitor (MOS capacitor, Figure 2) consists of semiconductor material which is covered by a thin oxide layer. The oxide layer carries a metallic conductor layer. If a positive voltage is applied to the metal electrode of the MOS element, a space-charge region of stationary positive charges is created underneath the insulating oxide layer. In the event of incident light through the transparent, insulated electrode (front-side exposure) or through the substrate (rear-side exposure), the photoelectrically generated electrons collect in this area without being able to recombine or flow off.

A typical value for the capacitance of a photodiode and of an MOS capacitor is $0.1 \text{ fF}/\mu\text{m}$ ([1], [2]).

Figure 2: MOS capacitor working as an integrating photosensor

- 1 Electrode,
 - 2 Space-charge region,
 - 3 Silicon oxide,
 - 4 *p* silicon.
- A Electron,
B Hole.



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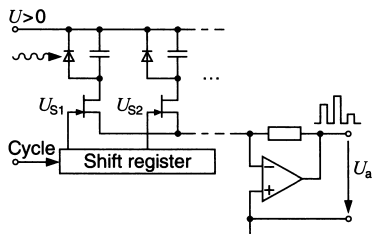
CCD imaging sensors

For the purpose of manufacturing imaging sensors (imagers), many photodiodes or MOS capacitors are interconnected into "arrays" with numerous pixels. While the output signals of photodiodes correspond to the instantaneous value of the luminous flux (illuminance), the following two structures are integrating in character. Their signal corresponds to the total number of photons which have penetrated the sensor during the exposure time. Such sensors are required primarily to manufacture line or uniplanar sensor arrays according to the CCD principle (charge-coupled devices).

In the case of these *pn* photodiodes, only a small part of the *pn* junction is radiation-sensitive on account of a vapor-deposited screen. The photoelectrically generated charges spread, however, to the entire space-charge region and are accumulated there. When a MOSFET switch is closed, they can flow off to a commonly used signal line (video output). The switch is controlled by a clock generator via a shift register (Figure 3). The charges flowing serially via the video line are a measure of the radiation dose of the photodiodes activated in each case.

To be able to shift the measurement charge laterally after exposure, further electrodes are as shown in Figure 4 arranged next to the exposable zone or the collector electrode; these electrodes are at zero potential during the integration phase. If the potential of a side transfer electrode is then increased to a positive

Figure 3: Line arrangement of photodiodes with serial output line



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value while the collector-electrode potential is simultaneously reduced, the charge can be shifted to a neighboring MOS element which is shielded by a screen against the incidence of light.

This principle of charge transfer forms the basis of charge-coupled devices (CCDs). According to this principle, analog charges can be shifted or transferred over many stations until they are finally converted at the end of the transfer chain by means of a charge amplifier, for example, into a voltage signal, which can be supplied to a fast analog-digital converter.

This method of charge transfer, which can also be viewed as a kind of analog shift register, facilitates the simple setup of long line-shaped multiple structures, but also of matrix-shaped structures. One single element of these structures is also called a pixel (contraction of picture element). As things stand today, the maximum possible number of pixels for line sensors is roughly 6,000, while that for matrix sensors is roughly $5,000 \times 5,000$, i.e. approximately 25 million. Today's imaging sensors in motor vehicles manage with under one million pixels. For more

sophisticated automotive applications, however, a much higher number of pixels would be desirable. In consumer applications cameras utilize imaging sensors with over ten million pixels.

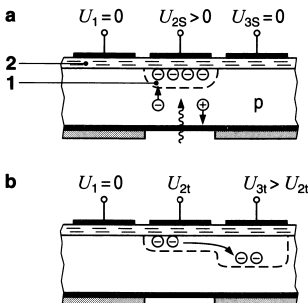
The size of the pixels which receive their light from a conventional imaging lens today lies typically in the range of 5 to 20 μm edge length. The chip surface of the sensor is thus in the cm^2 range. If the intention is to further reduce the individual pixels in size in order to increase the resolution or also to reduce chip costs, it is important to bear in mind that this will also mean a reduction in the number of incident photons per pixel. Thus, limits are placed on sensible reduction by the unavoidable noise process; the increased pixel resolution is then impaired by an increased noise level.

Even the charge that can be absorbed by the individual, integrating cells is limited. If this limit is exceeded, the charge can "spill over" into neighboring cells. This is also called the "blooming effect", which in principle limits the dynamic light/dark response of the CCD technology. Even with additional antiblooming protective measures, this dynamic response can barely be increased over a value of roughly 50 dB without additional aids such as a variable screen and exposure time.

Today, CCD imaging sensors are the most widely used semiconductor-based imaging-sensor technology. However, the limited dynamic light/dark response, the relatively high power requirement compared with other technologies at three different operating voltages, and the limited temperature range have restricted their wider use in automobiles.

Figure 4: MOS capacitor with rear-side lighting and transfer electrodes for charge transfer

- a) Collection of charge carriers by incident light,
- b) Transfer of charge carriers.
- 1 Space-charge region,
- 2 Silicon oxide.
- 0 $< U_{2t} < U_{2s}$.



CMOS imaging sensors

Today, CMOS imaging sensors represent a more forward-looking solution than CCD sensors, and are already widely used in many applications. The term "CMOS sensor" may be confusing here; this is because CMOS technology denotes a special semiconductor technology. CCD technology, on the other hand, does not need this, but also contains MOS structures. CMOS sensors essentially differ from their CCD counterparts not only in the manufacturing technology, but also in a range of features:

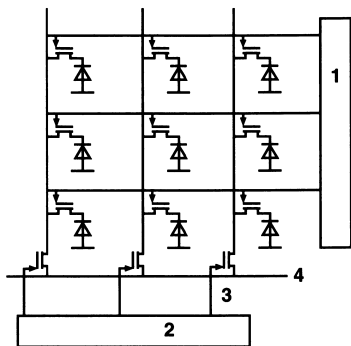
- The pixels are no longer read out serially; instead – similarly to a memory cell in a RAM or a pixel in an LCD flatscreen display – they are arranged in a matrix structure and can be individually activated. Active electronics are also integrated for each pixel for this purpose (APS, Active Pixel Sensor).
- Integrating photodiodes are not used; instead, those which are to a large extent not dependent on the exposure time are used.

- The brightness values are not proportionally converted into electrical signals; instead, they are logarithmized before being read out. They therefore have a similar characteristic to the human eye. Only through this measure is it possible to extend the dynamic light/dark response to more than 100 dB without additional measures.
- CMOS imaging sensors are not realized using standard CMOS technology. Instead, CMOS technology optimized to the photoelectric element is used which, because of the much lower power requirement than CCD sensors, allows further activation and evaluation electronics to be integrated on the imaging-sensor chip. Because the access time to the individual pixels is in the range of a few 10 ns, somewhat higher image frequencies are possible with CMOS sensors, particularly when use is made of the possibility of reading out subimages only (subframing), which is not possible with CCD sensors.

Figure 5: CMOS imaging sensor

Photodiode array with one photodiode and one activation transistor per pixel

- 1 Line addressing,
- 2 Column addressing,
- 3 Column selection,
- 4 Column signal line.



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Figure 5 shows an extract from a CMOS-imager structure. The individual pixel consists of a photodiode and a MOSFET (MOS field-effect transistor) as the switching element. Each individual pixel can be activated and read out via the matrix structure.

All photodiodes are charged to a bias countervoltage of around 5 V. The individual pixels are discharged to specific voltages under the influence of incident light. A pixel is read out by activating the associated line and column drivers, as a result of which a conductive connection is created from the pixel to the output amplifier. The pixel is then recharged via this connection to the original countervoltage. The amplifier measures the required charge for each pixel. This corresponds exactly to the photocharge which has been collected by the pixel. In this way, each pixel can be individually read out and the exposure time can be determined via the external addressing circuit.

A low noise level is achieved with this APS technology (Active Pixel Sensor), in which a MOSFET transistor is integrated in the matrix. The simplest APS pixel consists of a photodiode and three MOSFETs.

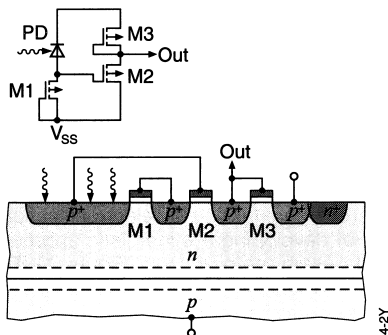
Figure 6 is a schematic representation of the structure of an HDRC pixel (High Dynamic Range CMOS technology). The light-sensitive element of this version of a CMOS sensor is a photodiode polarized in the blocking direction which is connected in series to the PMOS transistor (M1) operated below its opening voltage. The diode current proportional to the illuminance must also flow through the blocked transistor. Its gate-source voltage U_{GS} is dependent in a very wide range virtually ideally logarithmically on the drain current flowing through (photo-current). The other two transistors M2 and M3 serve to decouple the signal, which is supplied via a multiplexer to a fast 10-bit analog-digital converter.

References for video sensors

- [1] B. Jaehne, H. Haußecker, P. Geißler; (Ed.): Handbook of Computer Vision and Applications, Vol. 1. Academic Press, 1999.
- [2] P.M. Knoll: Ch. 7.8 "Video Sensors" in: J. Marek, H.-P. Trah, Y. Suzuki, I. Yokomori: Sensors for Automotive Technology. Wiley-VCH, Weinheim, 2003.

Figure 6: Schematic cross-section of an HDRC pixel

PD Photodiode,
M1, M2, M3 Transistors.



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Mechatronics

Mechatronic systems and components

Definition

The term “mechatronics” is a compound derived from the words mechanisms and electronics, where electronics means “hardware” and “software”, and mechanisms is the generic term for the disciplines of “mechanical engineering” and “hydraulics”. It is not a question of replacing mechanical engineering by “electronification”, but of developing a synergistic approach and design methodology (Figure 1). The aim is to achieve a synergistic optimization of mechanical engineering, electronic hardware and software in order to project more functions at low cost, less weight and installation space, and better quality.

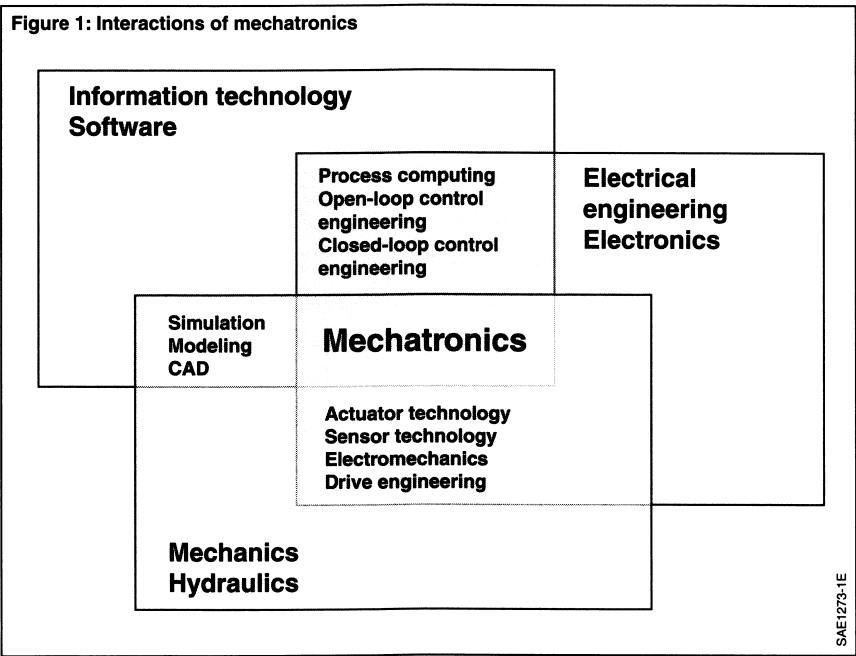
A crucial factor governing the success of a mechatronic approach to solving problems is to regard the two previously separate disciplines as a single entity.

Application

Mechatronic systems and components are now used in practically all aspects of the automobile today, starting with engine management and fuel injection for gasoline and diesel engines, transmission-shift control, and electrical and thermal energy management, through to a wide variety of braking and vehicle-dynamic systems. It even includes communication and information systems, with many different requirements when it comes to operability. Besides systems and components, mechatronics are also playing an increasingly vital role in the field of micromechanics.

Examples at system level

A general trend is emerging in the advanced development of systems for fully automated vehicle handling and guidance: In future, mechanical systems will be replaced to an increasing extent by “x-by-wire” systems. One system that has been



in existence for quite some time is "drive-by-wire", i.e. electronic throttle control. "Brake-by-wire" is replacing the mechanical and hydraulic link between the brake pedal and the wheel brake. Sensors detect the driver's brake command and transmit this information to an electronic control unit. The unit then generates the required braking effect at the wheels by means of actuators.

A possible option for implementing "brake-by-wire" is the electrohydraulic braking system (SBC, Sensoronic Brake Control). When the brake is operated or in the event of stabilization interventions by driving-dynamics control, the SBC ECU calculates the desired setpoint brake pressures at the individual wheels. Since the unit calculates the required braking pressures separately for each wheel and detects the actual values separately, it can also regulate the braking pressure to each wheel via the wheel-pressure modulators. The four pressure modulators each consist of an inlet and an outlet valve controlled by electronic output stages which together produce a finely metered pressure regulation.

In the common-rail system, pressure generation and fuel injection are separated from each other. A high-pressure accumulator, i.e. the common rail, stores constantly the fuel pressure required for each of the engine's operating states. A solenoid-valve-controlled injector with integrated nozzle assumes the function of injecting the fuel directly into the combustion chamber of each cylinder. The engine electronics constantly request data on accelerator-pedal position, rotational speed, operating temperature, fresh-air intake flow, and rail pressure in order to optimize the control of fuel metering as a function of the operating conditions.

Examples at component level

Fuel injectors are crucial components in determining future potential of diesel-engine technology. Common-rail injectors are an excellent example of the fact that an extremely high degree of functionality and, ultimately, customer utility can only be achieved by controlling all the physical domains (electrodynamics, mechanical engineering, fluid dynamics) to which these components are subjected.

In-vehicle CD drives are exposed to particularly tough conditions. Besides wide temperature ranges, they must withstand extreme vibrations that have a critical impact on such precision-engineered systems. The drives are usually equipped with a spring-damper system to isolate the playback unit from vibrations that occur when the vehicle is moving. Any considerations to reduce the weight and installation space of CD drives immediately raise questions concerning these spring-damper systems. If the damper system is eliminated from a CD drive, the main focus is on designing a mechanical system with zero clearances and producing additional reinforcement for the focus and tracking controllers at high frequencies. Only by considering both measures from a mechatronic viewpoint is it possible to achieve an optimized vibration-proof solution for an automotive environment. Besides weight savings of about 15%, the installation height has also been reduced by about 20%.

The new mechatronic approach for electrically driven coolant motors is based on brushless, electronically commutated DC motors. Initially, they are more expensive (motor with electronics) than previous motors equipped with brushes. However, the overall optimization approach has a positive tradeoff: Brushless DC motors can be used as "wet rotors" with a much simpler design. This reduces the number of single parts by roughly 60%. Taking the aggregate view, the sturdier design has double the service life, almost half the weight, about 40% less the overall length, while maintaining costs at a comparable level.

Examples in the field of micromechanics

Another area of applications for mechatronics is the field of micromechanical sensors, with noteworthy examples such as hot-film air-mass meters and yaw-rate sensors.

The design of microsystems also requires an interdisciplinary approach owing to the close interaction between the subsystems involving individual disciplines such as mechanical engineering, electrostatics, fluid dynamics (where necessary), and electronics.

Development methodology

Simulation

The special challenges that designers face when developing mechatronic systems are the ever shorter development times and the increasing complexity of the systems. At the same time it is vital to ensure that the developments will result in useful products.

Complex mechatronic systems consist of a large number of components from a wide range of physical domains: hydraulics, mechanical engineering, and electronics. The interaction between these domains is a decisive factor governing the function and performance of the overall system. Simulation models are required to review key design decisions, especially in the early development stages when there is no prototype available.

Basic issues can often be clarified by producing relatively simple models of the components. If more detail is required, more refined component models are needed. The detailed models focus mainly on a specific physical domain.

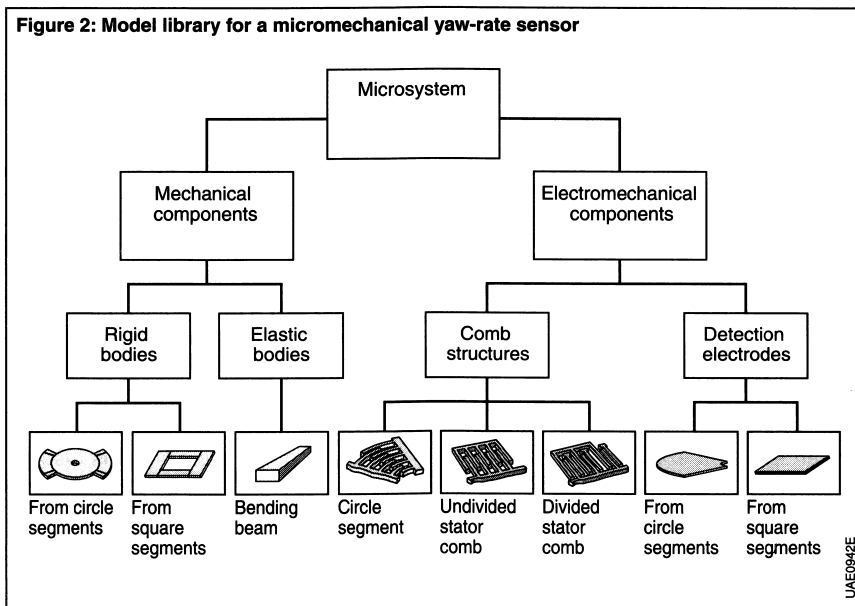
As a result, there are detailed hydraulic models of common-rail injectors. They are simulated using special programs whose algorithms are matched precisely to the hydraulic systems. For example, the requirements here would be to take cavitation phenomena into consideration.

Detailed models are also needed to design the power electronics for activating the injectors. Again, this involves the use of simulation tools which must be developed specifically to design electronic circuits.

Tools that are specially designed for this specific part of the overall system are also required to develop and simulate the control-unit software which controls the high-pressure pump and power electronics using signals from the sensors.

As the components in the overall system interact with each other, it is not sufficient to consider specific detailed models of the components in isolation. The optimum solution is also to take into account the models of other system components. In most cases, these components can be portrayed by much simpler models. For

Figure 2: Model library for a micromechanical yaw-rate sensor



example, a system simulation focused on hydraulics only requires a simple model of the power electronics.

The application of various domain-specific simulation tools during the design of mechatronic systems is only efficient if there is some sort of support for exchanging models and parameters between the simulation tools. The direct exchange of models is highly problematic due to the specific languages used for describing the models of each of the tools.

However, an analysis of the typical components in mechatronic systems shows that they can be composed of a few simple elements specific to the domains. These standard elements include, for example:

- in hydraulics: restrictor, valve, or pipe,
- in electronics: resistor, capacitor, or transistor,
- in mechanical engineering: mass with friction, transmission, or clutch (accordingly for micromechanics).

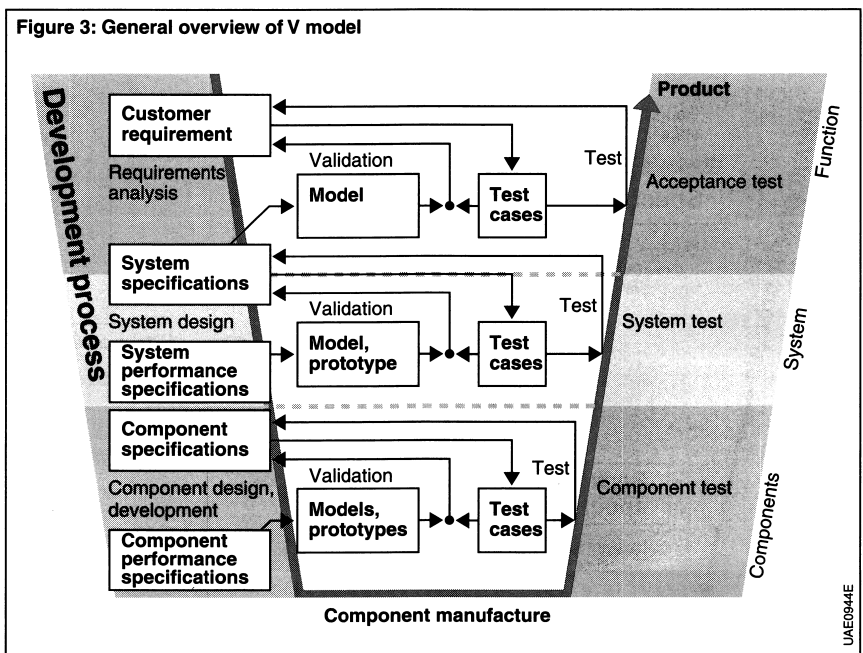
The preferable solution is that these elements should be stored in a central standard model library (Figure 2) that is also decentrally accessible to product development. The kernel of the standard model library is a documentation of all the standard elements. For each element, this comprises:

- a textual description of the physical behavior,
- the physical equations, parameters (e.g. conductivity or permeability), and state variables (e.g. current, voltage, magnetic flux, pressure),
- a description of the associated interfaces.

V model

The relationships between the different phases of product development are illustrated in the V model (Figure 3): from requirements analysis through drafting, development, implementation, and testing through to system introduction of the

Figure 3: General overview of V model



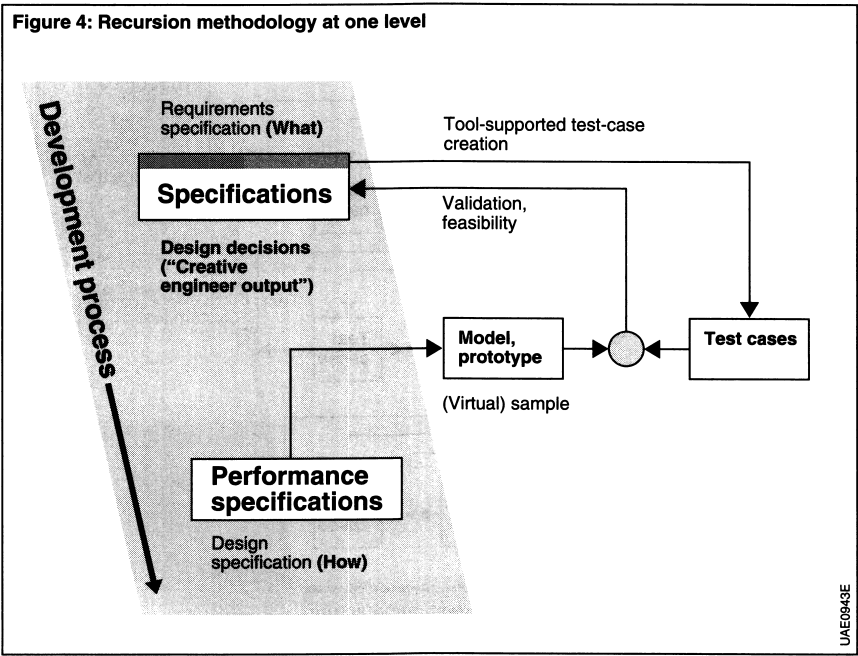
product. A project passes through three “top-down” levels during the development stage:

- customer-specific functions,
- system, and
- components.

A requirements specification (“what”) must first be produced at each level in the form of specifications (Figure 4). This is then used to produce the design specifications based on design decisions (the actual creative engineering output). The performance specifications describe “how” a requirement can be met. The performance specs form the basis for a model description which allows a review (i.e. validation) of the correctness of each design stage together with previously defined test cases. This procedure passes through each of three stages, and, depending on the technologies applied, for each of the associated domains (mechanical engineering, hydraulics, fluid dynamics, electrics and electronics, software).

Recursions at each of the design levels shorten the development stages significantly. Simulations, rapid prototyping, and simultaneous engineering are tools that allow rapid verification, and they create the conditions for shortening product cycles.

Figure 4: Recursion methodology at one level



Outlook

The driving force behind mechatronics is the continuous progress in microelectronics. Mechatronics benefits from computer technology in the form of ever more powerful integrated computers in standard applications. Accordingly, there is a huge potential for further increases in safety and comfort in motor vehicles, accompanied by further reductions in pollutant emissions and fuel consumption. On the other hand, engineers face new challenges in mastering the new technologies for these systems.

Even in the event of a fault, future “X-by-wire” systems must continue to be capable of fulfilling a prescribed functionality without reverting to a mechanical or hydraulic fallback level. The condition for their implementation is a high-reliability and high-availability mechatronic architecture which requires a “simple” proof of safety. This affects both single components as well as energy and signal transmissions.

Besides “x-by-wire” systems, driver-assistance systems and their related man-machine interfaces are another field in which significant progress can be achieved for users and automotive manufacturers by the systematic implementation of mechatronic systems.

The design approaches of mechatronic systems should strive toward continuity in several aspects:

- Vertical: “Top-down” from system simulation, with the objective of overall optimization, through to finite-element simulation to achieve a detailed understanding, and “bottom-up” design engineering from component testing through to system testing.
- Horizontal: “Simultaneous engineering” across several disciplines in order to deal with all product-related aspects at the same time.
- Across corporate boundaries: The concept of a “virtual sample” is approaching gradually step by step.

Another challenge is training in order to further an interdisciplinary mindset and develop suitable DE processes and forms of organization and communication.

Passenger-compartment climate control

Climate-control requirements

The system for controlling the climate in the passenger compartment of automobiles and commercial vehicles must fulfill many functions. Firstly, it must create a comfortable climate for all the occupants. To this end, cooled or heated air (depending on the outside temperature) is fed into the passenger compartment so as to meet the physiological needs of the occupants. A further function of climate control is to keep the passenger compartment free of unpleasant odors and pollutants.

Climate control also has the safety-related function of demisting and de-icing the windshield and side windows. Statutory requirements that vary from country to country must be met.

The comfort requirements and thus the functions of the A/C unit normally increase with the vehicle category. Regionally different climate-control requirements must also be taken into consideration. In Europe, for instance, vehicles with a system of climate control which is as unobtrusive as possible are preferred, whereas in the USA a cool, noticeable air current is desired.

Design and operating principle of the A/C unit

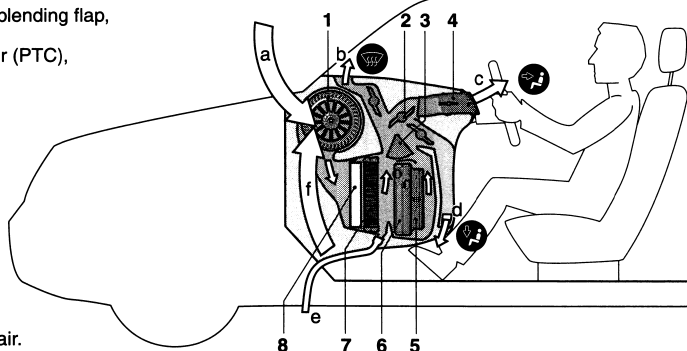
Air intake

The A/C unit is installed out of sight of the occupants under the vehicle's instrument panel. Fresh air is usually drawn in at the base of the windshield (Figure 1). Rain-water and snow are removed en route to the A/C unit. The outside air is drawn in by a radial fan and delivered through an opening in the bulkhead (partition between engine and passenger compartments). There is a further possibility of drawing in passenger-compartment air (recirculated air) through a second air inlet. The proportions of fresh air and recirculated air from the drawn-in air are controlled by flaps.

Fresh air is needed to supply oxygen to the passenger compartment. In recirculated-air mode, unpleasant odors and pollutants are prevented from entering the passenger compartment. In addition, power consumption is significantly reduced in recirculated-air mode, since the air to be temperature-regulated does not have to be heated and cooled so much in heating and cooling modes respectively. However,

Figure 1: Passenger-compartment climate control

- 1 Fan,
 - 2 Vent flaps,
 - 3 Temperature blending flap,
 - 4 Air vent,
 - 5 Electric heater (PTC),
 - 6 Radiator,
 - 7 Evaporator,
 - 8 Filter.
- a Fresh air,
b Air vent, windows (defrost),
c Air vent, ventilation,
d Air vent, footwell,
e Condensate drain,
f Recirculated air.



cold and thus dry fresh air must sometimes be used to prevent the windows from misting over due to condensation of damp passenger-compartment air.

Air cleaning

To clean the air, a sheet of filter fleece is pleated, i.e. folded, and preferably installed in the shape of a rectangular filter element before and after the fan in the A/C unit. The filter element is mainly positioned in such a way as to filter not only the fresh air, but also the recirculated air. The filter element has a limited retention capacity and must therefore be replaced. An activated-carbon layer can also be applied to the filter fleece (hybrid filter) in order to filter out particulates and pollutants.

Air cooling

The cleaned air is then cooled on the surface of an evaporator, which is now usually made entirely of aluminum. The air dissipates its energy proportionally to the evaporating refrigerant which is routed through the evaporator.

Because cold air can absorb less moisture than warm air, water is separated out as it cools and routed downwards along the evaporator. The water collects in the housing section under the evaporator, the condensate drip pan, and is discharged via the condensate outlet from the A/C unit to the atmosphere.

Air temperature regulation and distribution

After the evaporator the desired air temperature is set by a blending-flap system. To this end, the air is directed entirely or in part through a radiator (through which engine coolant flows) or – in pure cooling mode – past the radiator directly to the air vents. The air is continuously distributed to the two channels in any proportion by one or more temperature blending flaps. The cold and warm air currents are blended to suit demand in the downstream blending chamber. The air currents are blended in such a way as to cater for the comfort sensation of “cool head and warm feet”. For this purpose air is blown out at different temperatures at the three main “Footwell”, “Ventilation” (air vents in the instrument

panel) and “Windows” vent levels, generating temperature stratification of up to 15 K.

The volume of air blowing out of the individual vents is continuously adjustable to any proportion by hand or by motor-driven vent flaps.

In further expansion stages of the A/C unit additional vents can be provided for the rear passengers or temperature regulation of the passenger compartment can be set differently for different seats. The first expansion stage is two-zone temperature regulation. The interior temperatures on the driver and front-passenger sides can be set independently of one another. Three-zone climate control caters for the rear-seat area as an additional climate zone, while four-zone climate control provides for individual climate control for driver, front passenger and two passengers in the back.

A new feature is individual adaptation of the footwell temperature, or “variable stratification”. In this case, the outlet temperature in the footwell can be increased while the basic setting remains unaltered (for example for people with feet which are sensitive to cold).

Booster heater

In modern optimized-consumption internal combustion engines the waste heat available in the engine coolant is reduced, and thus with it the heat supply in the heating circuit. In this case, an electric PTC booster heater is installed in the air passage after the radiator. By using PTC ceramic heating elements (PTC, Positive Temperature Coefficient), the booster heater automatically reduces its heat output at a defined limit temperature, since the resistance of the PTC elements increases abruptly. The PTC booster heater is therefore intrinsically safe.

The utilization of further heat sources, such as heat recovery from exhaust gas for example, is currently being developed.

Air routing

The temperature-regulated air is directed through plastic blow-channels to the relevant vents. Window and footwell outlets are not adjustable. The blow direction (nozzles) and the air volume can be individually adjusted at the air vents.

Supplementary A/C units

In luxury-class vehicles supplementary A/C units are sometimes used for the rear passengers. These are designed either, like the main A/C units, as heater-coolers or as pure coolers, and are usually supplied with recirculated air. Supplementary A/C units are installed, for example, in the center console, above the rear wheel arch, in the spare-wheel recess, or behind the rear seat bench.

Alternative A/C-unit concepts

The A/C unit described above sets the desired temperature by blending cold and warm air and represents the standard design used today. Alternative A/C-unit concepts may be used in which the air after the evaporator is routed directly through the radiator. A valve can be used to steplessly adjust the water flow rate through the radiator and thus the desired level to which the air flowing through is heated. The blending-flap system for blending cold and warm air is omitted.

Because of the thermal inertia of the water-filled aluminum radiator, desired changes to the air outlet temperature can only be completed slowly. To ensure that the passenger compartment is quickly cooled with the maximum air mass, these concepts normally utilize an additional air-side bypass past the radiator.

The advantage of this concept is the slightly more compact design of the A/C unit and the possibility of shutting off the radiator on the water side and thus avoid the unwanted situation of the air being heated in cooling mode by hot components in the A/C unit. The disadvantage is the expense of integrating a water valve.

Regulation of climate control

The climate of the passenger compartment is controlled by making inputs at the A/C operating unit, by adjusting the air vents and – in more luxurious vehicles – by means of various sensors. The variations range from direct mechanical activation of the A/C unit via Bowden cables and flexible shafts to fully automatic, processor-controlled air conditioning, where only the desired temperature is set.

The variables that can be influenced are blow-out temperature, air flow rate, air moisture, and air distribution to the different vents. The secondary variables are interior temperature including temperature stratification, air flow, acoustics at each seat, and misting status of the windows.

Most people find the following configurations pleasant: in summer mode cold air from the vents in the instrument panel, in winter mode warm air from the footwell and defrost vents (for keeping the windows clear), and in transition mode, heated air in variable proportions from the defrost, footwell and ventilation vents in the passenger compartment. Additional influencing factors can play a part in automatic air conditioning. The status and intensity of the Sun can be determined by solar sensors and included in the control operation. Air-quality sensors detect pollutants and odors in the ambient air and prevent them from entering the passenger compartment by closing the fresh-air inlets. Moisture sensors for the windshield enable action to be taken to prevent imminent window misting. The desired and actual passenger-compartment temperatures are compared by of temperature sensors.

Climate-control systems

Heating circuit

The waste heat from the engine is a source of energy which can be utilized without great expenditure to heat the passenger compartment. The hot coolant flows through the radiator in the A/C unit. The air passing through the radiator is heated.

In order to maintain the interior temperature in winter after a journey when the engine is switched off, it is possible to use an electric water pump, which forwards the coolant and makes the heat stored in the cooling system usable.

Refrigerant circuit

The function of the refrigerant circuit is to absorb the thermal energy of the air to be cooled in the evaporator and dissipate it at another point, outside the passenger compartment, to atmosphere. This is effected by using the cold-loss process in a closed refrigerant circuit (Figure 2). The main components of this circuit are the evaporator with expansion valve in the A/C unit, the condenser at the front of the vehicle, usually mounted directly in front of the coolant radiator, and the compressor secured to the engine block and driven by the engine.

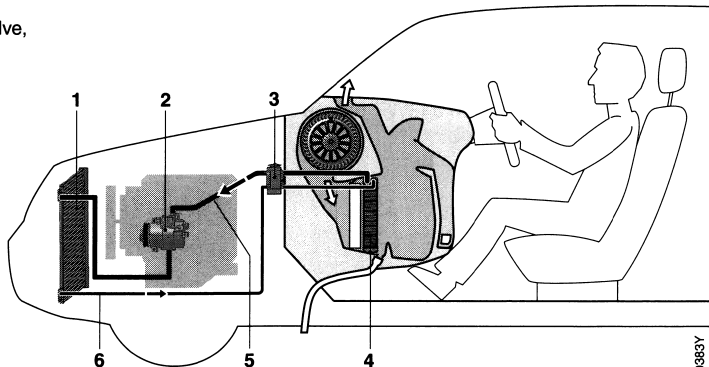
The components are connected by metallic pipes which can contain flexible sections for decoupling. The compressor draws the gaseous refrigerant from the evaporator and compresses it, i.e. the pressure and temperature levels are greatly increased. In the condenser the hot refrigerant dissipates heat to the ambient air flowing through the condenser. This cooling condenses the vapor-state refrigerant. If the air stream is not enough to cool the refrigerant sufficiently, the radiator fan increases the air flow rate through the condenser. The refrigerant – now in liquid form and under high pressure – is atomized in the expansion valve and directed to the evaporator. The pressure level drops suddenly, as a result of which the refrigerant is highly cooled as it evaporates, and absorbs the heat of the air to be cooled in the A/C unit.

The evaporated refrigerant exits the evaporator in gaseous form and passes the expansion valve again, which, on the basis of the pressure and the temperature of the exiting refrigerant, alters the throttling cross-section on the inlet side so as to inject into the evaporator just that amount of refrigerant that can evaporate in the current operating state.

The cold gaseous refrigerant is drawn in again by the compressor and the circuit begins afresh.

Figure 2: Climate-control refrigerant circuit

- 1 Condenser with integrated refrigerant collector and dryer,
- 2 Compressor,
- 3 Expansion valve,
- 4 Evaporator,
- 5 Intake line,
- 6 Pressure line.



In order to prevent ice from forming on the air side of the evaporator, which would reduce the evaporator air cross-section, the minimum air temperature must not drop below 0°C. To measure the air temperature after the evaporator, either an air-temperature sensor is used which regulates the compressor accordingly if the temperature drops below a fixed level, or the minimum intake pressure and thus the evaporator temperature are limited in the compressor. The refrigerant output can be adjusted between zero kilowatts (refrigerant does not flow through the evaporator) and a maximum output of approx. 8 kilowatts (for maximum refrigerant quantity and air flow rate).

Refrigerant

The fluorocarbon 1,1,1,2-Tetrafluorethane, which goes by the trade name R134a, is used as the refrigerant for vehicles with homologation before 2011-01-01 or vehicles where an existing type approval has been expanded (see Refrigerants, Operating fluids).

Because of this refrigerant's GWP (Global Warming Potential) of approx. 1,400 and the statutory provision which will come into force in Europe in 2011, which prescribes a refrigerant with a GWP of less than 150 for new vehicle models, an alternative refrigerant must be used here. There is currently still a lively debate regarding applicability of the alternative refrigerants. 2,3,3,3-Tetrafluoropropene with the trade name R-1234yf and carbon dioxide with the trade name R-744 are being pursued as alternatives. Starting at 2017-01-01 in Europe, all newly approved passenger cars must use a refrigerant with a GWP of less than 150.

Climate control for hybrid and electric vehicles

In vehicles with an engine start/stop function, it is necessary to keep the interior climate constant when the engine is switched off. For heating, an electric water pump can be used to utilize the residual heat from the engine circuit. For cooling, evaporators have been developed with a cold accumulator on the basis of a material which can store cold by means of a phase change and dissipate it again when stopped at traffic lights with the engine switched off. The interior climate can thus be kept at a pleasant level for up to two minutes.

In vehicles which run partly or entirely on electricity, a compressor is used which is electrically powered. Two solutions are available for heating. Either the water required for the radiator is electrically heated and supplied to the circuit by an electric pump, or the radiator is replaced by an electric heating element, the high-voltage PTC. Electric heater and electric compressor also open up the possibility of independent climate control. When the battery is sufficiently charged or connected to a charging station, the vehicle can be both preheated and precooled.

Because the power required for climate control can amount to several kilowatts and thus the range of an electric vehicle is reduced significantly, current developments are focused on increasing the efficiency of climate control.

Cabin filters

Function

Heating and air-conditioning systems in motor vehicles draw in air from the outside. After conditioning, the air passes into the passenger compartment together with any particles or gaseous pollutants it may contain. These air pollutants (Figure 3) can cause allergic reactions. Therefore, it makes sense to filter out particles and gases. A filter also reduces the amount of dirt that builds up on the fan, in the heating system, on the instrument panel, and on the inside of the windshield.

Depending on the requirement, either particle filters, charcoal filters, or biofunctional filters are used. Charcoal filters have the advantage that, besides filtering out particles, they can also prevent unpleasant odors from entering the passenger compartment. This is achieved by carefully embedding activated charcoal granules (up to 300 g/cm²) on the particle-filter medium to eliminate aromatic substances. The activated charcoal also adsorbs ozone, benzene, and toluene, for instance. Biofunctional filters are furthermore used to prevent the growth of bacteria and to retain allergenic proteins.

Filter media

Whereas in the past filter media were primarily paper-based, the situation has now changed as a result of the greater demands placed on the filter system (removal of particles smaller than 0.001 mm). Present-day

filter media generally consist of polyester or polypropylene-based nonwoven materials. The particle filter consists of three graduated fiber layers: the preliminary filter, the microfiber nonwoven layer with electrostatically spun microfibers, and the base nonwoven material. An activated charcoal filter also has an activated charcoal layer in addition to the three fiber layers. In a biofunctional filter a special coating on the filter medium provides the biofunctional effect.

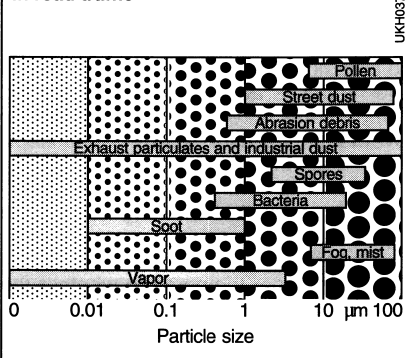
When the filter material is made into a filter, a number of specific parameters must be considered. There is a complex interrelationship between the filter material used, the depth of the filter-element folds, and the distance between the folds. The interaction between these parameters is important in determining the filter performance in service.

Design

Cabin filters must be optimized in three areas: filtration efficiency, pressure loss, and dust-storage capacity. The specifics of the application determine which of these three considerations is given precedence. The best filter may, for example, be a filter that achieves the highest possible filtration efficiency at the expense of a tradeoff in the filter service life. Another filter design may be one where a long service life is achieved by a high dust-storage capacity at a defined level of filtration.

The service life of filters used in passenger cars is around 20,000 km, i.e. with today's servicing intervals, they are replaced each time the car is taken for a scheduled service.

Figure 3: Prevailing particle sizes in road traffic



Auxiliary heater systems

Function and designs

Auxiliary heater systems use the fuel carried in the vehicle's tank to generate heat. Air heaters (Figure 4) are used to heat the passenger compartment directly. They transfer the heat generated during combustion to the cabin air. Coolant heaters (Figures 5, 6, 7) introduce heat into the cooling water and are thus suitable both for preheating engines and for heating the passenger compartment via the vehicle's heat exchanger with blower.

Air heaters are particularly efficient due to the direct transfer of heat to the air and are suitable for long periods of heating. Coolant heaters use the cooling circuit and the vehicle's existing air ducts and are therefore particularly suitable for covering the heat deficit of low-consumption drives and for preheating the passenger compartments and engines of passenger cars.

Further advantages of auxiliary heater systems are:

- Ice-free windows thanks to preheating,
- Optimized heating comfort,
- Use of a truck sleeping cabin even in winter,
- Less wear and lower emissions when starting with a preheated engine (with coolant heater only),
- Operating temperature of the catalytic converter reached more quickly (with coolant heater only).

Of increasing importance is their use in passenger cars with deficient heat output from waste heat caused by increased drivetrain efficiency by means of electrification. Particularly in plug-in hybrid vehicles – but also in purely battery-powered vehicles – fuel-powered heaters, on account of their great efficiency in converting chemically bound energy into heat, ensures that the range in electric driving mode is not limited in the case of the storage capacity of the traction batteries being specified.

Air heaters

Application

Air heaters are primarily used in trucks and commercial vehicles. Their main advantages are low costs, faster installation, and lower power and fuel consumption. A dramatic increase in their use was witnessed in the USA with the introduction of legislation prohibiting the running of the engine to provide heat during breaks in driving since heaters can heat the cabs with clearly lower fuel consumption.

Operating principle

Air heaters (Figure 4) operate independently of the vehicle's own heat balance. A combustion-air blower draws the air required for combustion from the surrounding atmosphere, and blows it into the burner. An electric metering pump delivers diesel or gasoline as fuel via an evaporator (component not visible in Figure 4) to the burner, where it mixes with combustion air, is ignited by a sheathed-element glow plug, and burns. The heating-air blower draws in the fresh air to be heated, blows it through a heat exchanger, and into the vehicle cabin.

In cold countries a heat output of approx. 4 kW is required. In temperate climates units with approx. 2 kW are sufficient.

An important safety aspect is that combustion air and exhaust gas from the cabin air must be kept entirely separate. This prevents exhaust gas from entering the cabin.

The heat output is regulated by varying the quantity of fuel, combustion air and fresh air. If the temperature measured by the room-temperature sensor deviates from what is set at the operating element (e.g. radio remote control), the output of the heater is adapted until the desired temperature is reached once again. An overheating sensor registers unacceptable temperatures through defects or malfunctions that occur (e.g. overheating due to blocked heating vents) and switches off in good time if necessary. A flame sensor determines by means of the heat-exchanger temperature whether the burner has ignited and detects when the flame goes out.

Installation

Air heaters for commercial vehicles can usually be fitted directly inside the cab. In trucks, for instance, the preferred locations are in the co-driver's footwell, on the rear cab wall, under the bunk bed, on the outside of the cab wall, or in a stowage compartment. The exhaust pipe always runs under the floor (either into the wheel arch, or out of the rear cab wall).

Most sensor units in the fuel tanks of passenger cars and trucks already have a connection available for supplying fuel to the air heater. If necessary, an extra tank sensor unit is fitted. A fuel reserve for driving is guaranteed by the immersion depth of the fuel-tank extraction fittings or the vehicle electronics, which switches off the heater from a minimum fill level.

Coolant heaters

Application

Coolant heaters up to approx. 5 kW heating capacity are used both in passenger cars and in trucks. They use the cooling circuit and already existing heat exchangers to heat the engine and cabin, as well as the available fans, air ducts, flaps, and vents. They are thus easy to retrofit. Heaters up to approx. 12 kW are used in trucks to preheat the engine. The large body surface area and high interior volume of city and tour buses mean that they require heating capacities of up to 35 kW.

The main types are auxiliary and booster heaters for passenger cars. These heaters are integrated directly in the cooling-circuit feed line between the engine and the heat exchanger of the passenger

Figure 4: Air heater

- 1 Heating-air blower, 2 ECU, 3 Combustion-air blower, 4 Sheathed-element glow plug,
- 5 Heat exchanger, 6 Combination sensor (overheating and flame sensor),
- 7 Radio remote control (mobile part), 8 Radio remote control (stationary part),
- 9 Button, 10 Room-temperature sensor, 11 Fuse holder, 12 Electric motor,
- 13 Burner, 14 Metering pump, 15 Exhaust muffler.

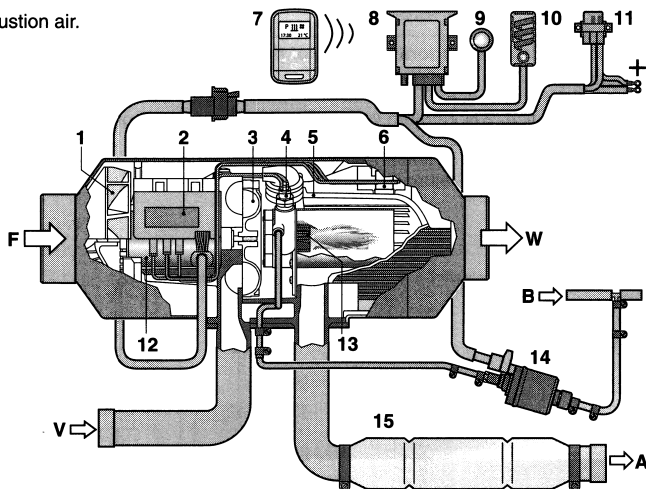
F Fresh air from vehicle cabin,

W Hot air to vehicle cabin,

A Exhaust gas,

B Fuel,

V Combustion air.



cell (Figure 5). They utilize the existing devices: vehicle heat exchanger with blower, air flaps and vents.

Quick-starting heaters are used to meet high demands with regard to heating-up speed; these reach their full heat output level after approx. 30 s. The required acceleration of fuel vaporization is achieved by heating the vaporizing apparatus electrically during the starting sequence.

Auxiliary heaters for preheating engine and passenger compartment before starting driving

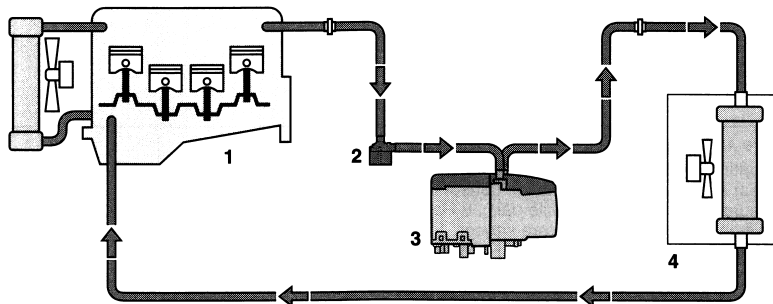
Heat is generated through combustion of fuel along similar lines to air heaters. The generated heat is transferred to the cooling water flowing between the water jacket and heat exchanger (Figure 7) of the heater.

The simplest method of integrating them in the vehicle's cooling system is to

Figure 5: Coolant heater, integrated in cooling circuit

(Standard type)

- 1 Internal-combustion engine, 2 Water pump, 3 Coolant heater, 4 Vehicle heat exchanger with blower.



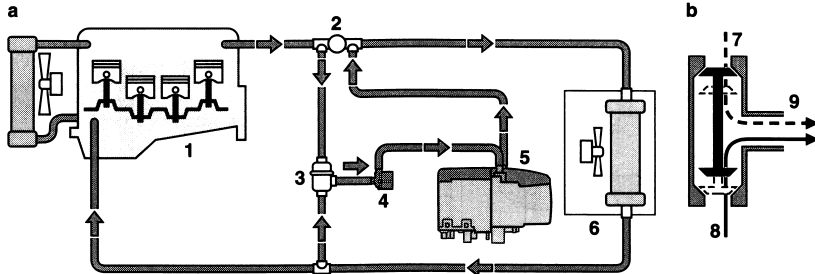
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Figure 6: Split cooling circuit for priority heating of passenger compartment

(Split into secondary and primary cooling circuits)

a) Layout, b) Thermostat connections.

- 1 Internal-combustion engine, 2 Non-return valve, 3 Thermostat, 4 Water pump, 5 Coolant heater, 6 Vehicle heat exchanger with blower, 7 Return flow from vehicle engine, 8 Return flow from heat exchanger, 9 Connection to heater. Separation by thermostat and non-return valve into small water circuit (priority for interior heating) and large water circuit (with motor).



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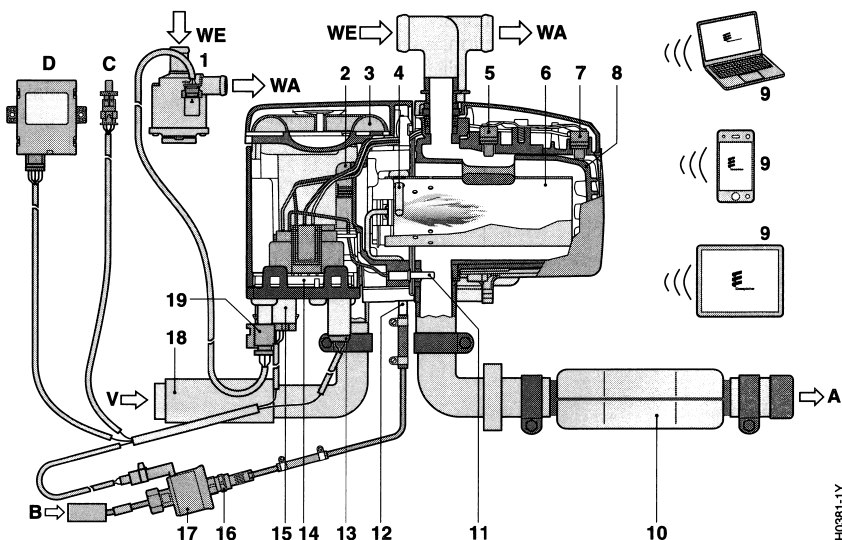
connect them in series between the engine and the heat exchanger in the primary circuit (Figure 5). A disadvantage with engines over approx. 2.5 l is that engine heating makes heating the passenger compartment much slower. In this case, the passenger cell can be heated as a matter of priority via an additional small circuit (Figure 6). This offers, irrespective of the engine, the advantage of being able to use the heating also for short-distance service without discharging too much the starter battery, which during the starting phase powers the glow element, the burner fan, the water pump, and the metering pump. Flow

passes through the engine only after the thermostat opens when a high water temperature is reached. The non-return valve prevents the circuit from being bypassed via the thermostat.

The water pump (Figure 7) in auxiliary heaters pumps cooling water to the heating-system heat exchanger, where it is heated by heat transfer by the burner exhaust gas. On the one hand, the heated water preheats the vehicle engine; on the other hand, the vehicle's own heat exchanger (Figures 5 and 6) dissipates the heat. The heated air is blown controllably through the existing ventilation system into the vehicle cabin.

Figure 7: Coolant heater

- 1 Water pump, 2 Combustion-air motor, 3 Fan wheel, 4 Glow element, 5 Temperature sensor,
6 Burner, 7 Temperature sensor, 8 Heat exchanger,
9 Web-based operating elements (laptop, smart phone, tablet),
10 Exhaust muffler, 11 Flame sensor, 12 Fuel connection,
13 Plug-in connection, blower-flap control module, 14 ECU, 15 Connection to heater,
16 Pot strainer, fitted in metering pump, 17 Metering pump, 18 Combustion-air muffler,
19 Water-pump connection,
A Exhaust gas,
B Fuel,
C Diagnosis connection,
D Blower-flap control module,
V Combustion air,
WA Water outlet,
WE Water inlet.



Control for manual immediate operation and for preprogramming switch-on times and heating duration is performed via radio remote control, via the Internet for example by means of a smart-phone app, or via a menu in the vehicle's own A/C operator unit.

Booster heaters for covering heat deficits while driving

Efficiency-optimized drivetrains, such as highly turbocharged diesel and gasoline engines with small displacements and hybrid drives, generate on account of their efficiency insufficient waste heat to heat the passenger compartment. Booster heaters are used to make up this heat deficit. They operate only at outside temperatures below +5 °C and when the engine is running. They therefore do not require their own water pump.

Booster heaters can be upgraded to an auxiliary heater by retrofitting a water pump and a control element with ECU.

When used in an electric vehicle or in a plug-in hybrid vehicle, the fuel-powered heater can cover the entire heat demand.

Installation

To avoid heat losses through long cooling-water hoses, coolant heaters are usually installed in the engine compartment. The confined installation conditions necessitate a very compact construction. Installation is simplified by integrating all the components required to generate and deliver heat in the heater unit (Figure 7).

Regulations

All auxiliary heaters and booster heaters run on fuel have type approval in accordance with ECE Regulations No. 10 [1] and No. 122 [2].

If a heater with this type approval is retrofitted in line with the manufacturer's installation instructions, no inspection/approval by an expert or inspection body is prescribed. The installation of auxiliary heaters in vehicles used for international transport of hazardous goods is governed by the European ADR agreement (Accord européen relatif au transport international des marchandises Dangereuses par Route). The heater must be switched off for safety reasons before the vehicle enters a hazardous area (e.g. refinery or filling station). The heating also switches off automatically as soon as the vehicle engine is shut down or an ancillary (e.g. auxiliary drive for discharge pump) is switched on.

Regulations in the USA

The heater requires CARB approval (emissions certificate) for installation and operation in medium and heavy commercial vehicles.

References

- [1] ECE R 10: Regulation No. 10 of the Economic Commission for Europe of the United Nations (UN/ECE) – Uniform provisions concerning the approval of vehicles with regard to electromagnetic compatibility.
- [2] ECE R 122: Regulation No. 122 of the Economic Commission for Europe of the United Nations (UN/ECE) – Uniform technical provisions concerning the approval of vehicles of categories M, N and O with regard to their heating systems.

Comfort and convenience systems in the door and roof areas

Power-window systems

Power windows have mechanisms that are driven by electric motors. There are two types of design in use (Figure 1):

- Arm window lift: The window-lift-drive pinion engages with a quadrant gear, which is connected to a rod linkage. This system is highly efficient. On the down side, the system requires a large amount of space for fitting and is heavy.
- Flexible cable window lift: The window-lift drive turns a cable reel, which operates a flexible cable mechanism. Systems with two guide rails are used for the most part in front doors. Systems with one guide rail are preferred in rear doors. A crucial advantage of these designs is their excellent ability to guide the window glass.

Power-window drive

The power-window drive consists of a DC motor with downstream reduction gearing (Figure 2). For comfort and safety reasons, many power-window drives are equipped with an ECU. The gearing is designed as a helical bevel gear to create the necessary self-inhibiting effect which prevents the window from opening inadvertently of its own accord or being opened by force. Special tribological measures and the magnetic-circuit configuration of the DC motor further improve the drive's self-inhibiting properties. Space limitations inside the door make narrow (flat) drive units imperative.

Dampers integrated in the gearing mechanism provide good damping characteristics at the window-glass end positions.

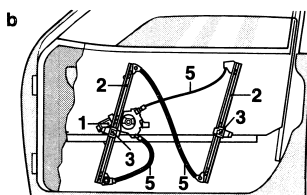
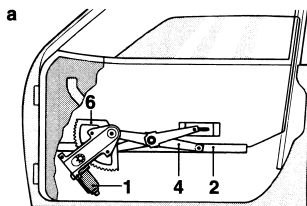
Electronic control unit (ECU)

Two different operating modes are used. In manual mode the power-window drive is operated using a switch which is pressed over the full extent of window travel. In automatic mode the window glass is opened or closed by a short pressing of the switch.

A force-limitation device is required by law to avoid injuries in the course of au-

Figure 1: Power-window systems

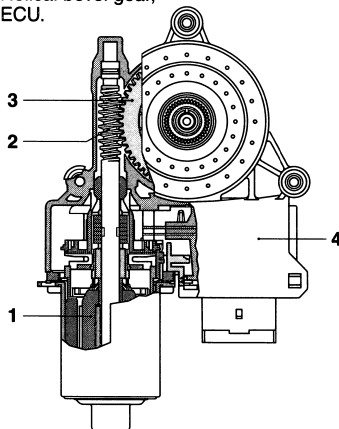
- a) Arm window lift, b) Flexible cable window lift.
1 Power-window drive,
2 Guide rail,
3 Driver,
4 Rod linkage,
5 Drive cable (Bowden cable),
6 Quadrant gear.



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Figure 2: Power-window drive with integrated ECU

- 1 Power-window drive motor,
2 Worm,
3 Helical bevel gear,
4 ECU.



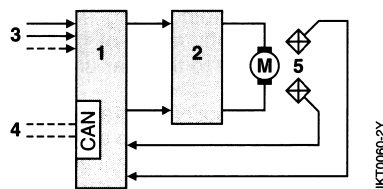
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tomating closing. In Germany, paragraph 30 of the StVZO [1] (Road Traffic Licensing Regulations) stipulates that the force-limitation device must be effective when the window is moving upwards within a range of 200 to 4 mm from the upper edge of the window aperture. The power-window drive includes integral Hall sensors to monitor motor speed during operation (Figure 3). If a drop in speed is detected, the DC motor's direction of rotation is immediately reversed. The window closing force, measured for a spring rate of 10 N/mm, must not exceed 100 N. To be able to close the window safely, the force-limitation device is automatically deactivated before the window glass enters the door seal. The window position is monitored over its entire range of movement.

Depending on the vehicle topology, the electronic control may be accommodated in a central ECU or decentrally in the door,

Figure 3: Power-window control unit featuring electronic force-limitation device

- 1 Microcomputer,
- 2 Relay output stage,
- 3 Control commands,
- 4 Networking via CAN,
- 5 Hall sensors.



preferably directly in the power-window drive. Decentralized electronics can be networked via a LIN-bus interface. The advantages of such a solution are fault diagnosis of the electronics and reduction of the amount of wiring.

Sunroof systems

Design variations

Power-sunroof drives can combine tilting- and sliding-sunroof functions. Three different types of sunroof systems may be used:

- The simple sliding/tilting sunroof: A panel (frequently made of glass) can be tilted or slid to the rear underneath the roof skin.
- The large sunroof or panoramic sunroof: This system utilizes up to three sliding-sunroof drives with different adjustment options (Figure 1, e.g. adjusting a glass panel in the front and rear areas, or with a fixed glass panel and an electrically adjustable roller sun blind).
- The spoiler sunroof: Here the glass panel is tilted and then moved to the rear over the roof skin (hence the term “spoiler”).

Power-sunroof drives

Sunroofs and roller sun blinds are primarily adjusted by means of torsion- and pressure-resistant control cables or plastic toothed straps with mechatronic drives. These are located in the roof between the windshield and the sliding sunroof or at the rear of the vehicle.

In the event of an electric-adjustment failure, the sunroofs can be closed by means of a hand crank provided on the drive.

The drive consists of a permanent-field DC motor with helical gear drive, a power output of approximately 30 W and an ECU. The motor is protected against thermal overload by software thermal protection.

Electronic control

The electronic control system operates with a microcomputer responsible for evaluating incoming signals and monitoring sliding-sunroof position.

Control is provided by means of exact position pulses. The pulses come from the ring magnet (up to 12-pole), which is mounted on the motor armature. They are sensed and evaluated by two Hall-effect switches. As well as exact positioning, it is also possible to effect closing-force limitation in order to avoid injuries during automatic operation when both opening and closing.

The drive is actuated via external signal inputs using pushbuttons, switches, and analog or digital preselector switches (e.g. potentiometers, digital sensing via Gray code).

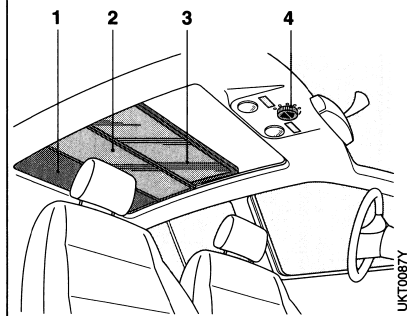
Control can be integrated in the vehicle's bus system (CAN, LIN) and diagnostic information can be output. Electronic control offers the opportunity to easily implement a wide range of functionalities and comfort and convenience functions (e.g. preselectable position control, closing via remote control, automatic closing in the event of rain, combination with the central locking system).

References

- [1] German Motor Vehicle Safety Standards (StVZO) – § 30 Beschaffenheit der Fahrzeuge (State of vehicles).

Figure 1: Panoramic sunroof with operating facility

- 1 Sliding roller sun blind,
- 2 Fixed or sliding glass panel in rear area,
- 3 Sliding glass panel in front area,
- 4 Operating unit.



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Comfort and convenience functions in the passenger compartment

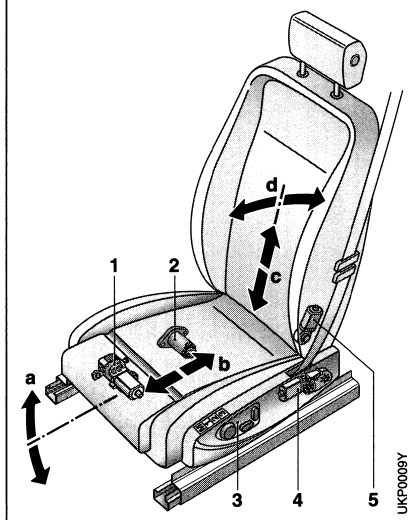
Electrical seat adjustment

On the one hand, the electrical seat adjustment ensures greater operating convenience than mechanical operation, and, on the other hand, it is also preferred on account of its lower space requirement or in the case of poor accessibility of the various adjustment planes.

The four main adjustment planes feature longitudinal adjustment of the full seat, tilt adjustment of the seat backrest, and height and tilt adjustment of the seat cushion.

Figure 1: Electromechanical seat adjustment

- 1 Electric motor for longitudinal adjustment of the seat (gearing is part of the seat structure),
- 2 Electric drive for height adjustment,
- 3 Operating unit (on the seat or alternatively in the door),
- 4 Electric drive for tilt adjustment of the seat cushion,
- 5 Electric drive for tilt adjustment of the seat backrest,
- a Tilt adjustment of the seat cushion,
- b Longitudinal adjustment of the full seat,
- c Height adjustment of the seat,
- d Tilt adjustment of the seat backrest.



Drives

Electric motors with different gear variants are used (e.g. lifting and rotating spindles, planetary gears, and two-stage spur gears) are used as drives for electrical adjustment.

To simplify entry and exit, the drives can be designed in such a way that adjustment is completed particularly quickly (easy entry). This function is particularly useful for gaining access to the second row in a two-door vehicle.

Position detection

Drives with position detection are increasingly being used to enable the seat position to be stored individually for different drivers and to retrieve and adjust this position (memory function). Position detection is effected either via Hall generators or via sensorless evaluation of the current signals from the electric motor (also called Sensor Less Control, SLC).

The memory function simplifies and speeds up adjustment of the seat position for an individual driver after a change of driver.

Further adjustment options

Aside from the four main adjustment planes for the driver and the front passenger, a wide range of additional adjustments can be performed electrically such as seat-cushion depth, head restraint, and lumbar support.

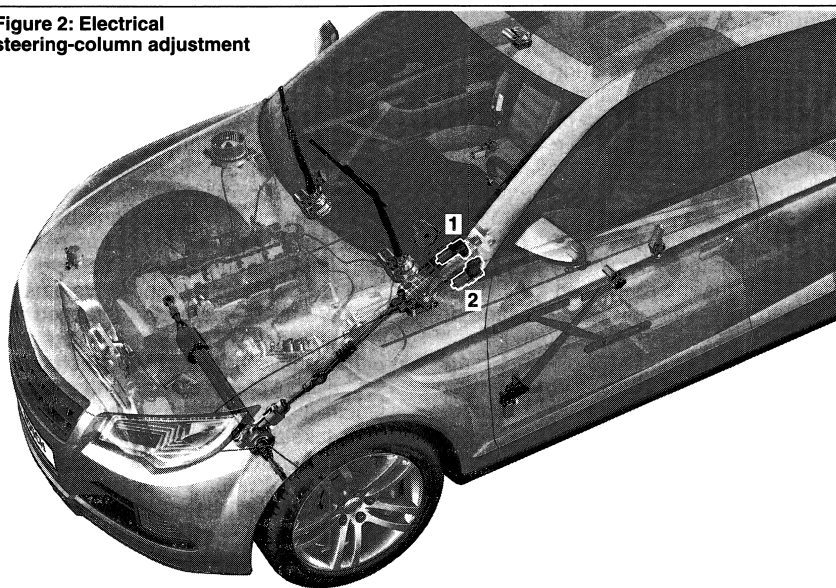
Electrical adjustments are increasingly also being performed for the second and third seat rows in larger vehicles (e.g. off-road vehicles). A significant motivation for this is to make it much easier and more convenient to load larger objects.

Electrical steering-wheel adjustment

A further comfort and convenience function which is often combined with electrical seat adjustment is electrical steering-wheel adjustment. Here both the longitudinal clearance and the height of the steering wheel can be infinitely adjusted via a drive similar to the spindle drives for seat adjustment.

This function is particularly useful in combination with the memory function. In this way, for example, entry and exit are made easier by extending the clearance between the driver's seat and the steering wheel prior to entry and exit. During driving the positions of the seat and steering-wheel adjustments individually preprogrammed for the driver are set.

Figure 2: Electrical steering-column adjustment



- 1 Electrical steering column height adjustment drive,
- 2 Electrical steering column longitudinal adjustment drive.

Display and control

Interaction channels

Drivers have to process a constantly increasing stream of information originating from their own and other vehicles, from the road, and from telecommunication equipment. All this information must be conveyed to drivers on suitable display and indicating equipment that complies with ergonomic requirements.

Visual channel – seeing

A human being discerns their environment predominantly through their sense of sight (Figure 1). Other road users, their position, their suspected behavior, the lane, and objects in the road area are detected with the human being's sight apparatus and their subsequent highly powerful image processing and interpretation, selected and evaluated by further structures in the brain with regard to their development and relevance.

Road-traffic infrastructure makes demands on above all the visual channel: Road signs communicate rules, markings delimit lanes from each other, direction-indicator lamps indicate a change of driving direction, stop lamps warn against vehicles that are slowing down. The visual channel is therefore extremely important to the driving environment.

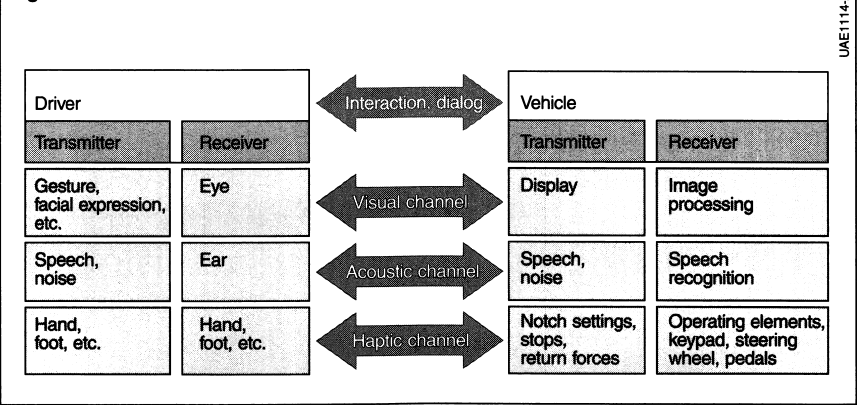
This applies to conscious vision, whereby the driver turns their eyes specifically to objects and focuses on them, but also to peripheral vision, which is crucial to positioning the vehicle within the lane. For this reason, additional glances at displays in the vehicle during interaction with driver-information and driver-assistance systems or their monitoring must be carefully assessed as to possible effects on road safety.

Acoustic channel – speaking and hearing

For communication with other road users, particularly the display and signaling of danger, the acoustic channel is used by human beings and by driver-assistance systems. In the driver's own vehicle this channel is also used to input commands via speech input systems and to output warnings and information from the driver-assistance system to the driver with acoustic signals and speech output.

The input of voice commands does not require the driver to turn their eyes, but does take up the driver's attention. Hearing does not require the driver to turn their eyes, but can convey spatial and complex information (e.g. description

Figure 1: Information channels between driver and vehicle



of the situation at intersections) poorly. Even drivers who do not have an adequate sense of hearing must be able to communicate with the driver-assistance system.

Haptic and kinesthetic channels – operation and feeling

The haptic channel provides feedback to the driver in the case of all motor operations when switches are operated and during steering and braking. Warning the driver by tightening their seat belt briefly and by vibrating the seat in the event of an imminent departure from the present lane has already been introduced in series production. A further possibility for arousing the driver's attention is the vibration of the steering wheel. Increased resistance on the accelerator pedal can support a speed recommendation and heightens the driver's attention. A torque that the driver can feel can be exerted on the steering wheel to suggest an evasive maneuver.

Even the kinesthetic channel, which helps the driver to perceive instances of acceleration while driving, is already in use in production vehicles for the purpose of arousing the driver's attention, for instance by way of a short braking jolt.

The haptic channel is however continuously required for steering and cruise control, and additional manual operations (e.g. operation of the cellular phone's keypad) may impair lateral guidance by distracting the driver.

Instrumentation

Information and communication areas

In any vehicle, there are four information and communication areas which must satisfy different requirements in terms of their display features: the instrument cluster, the windshield, the center console, and the rear cabin.

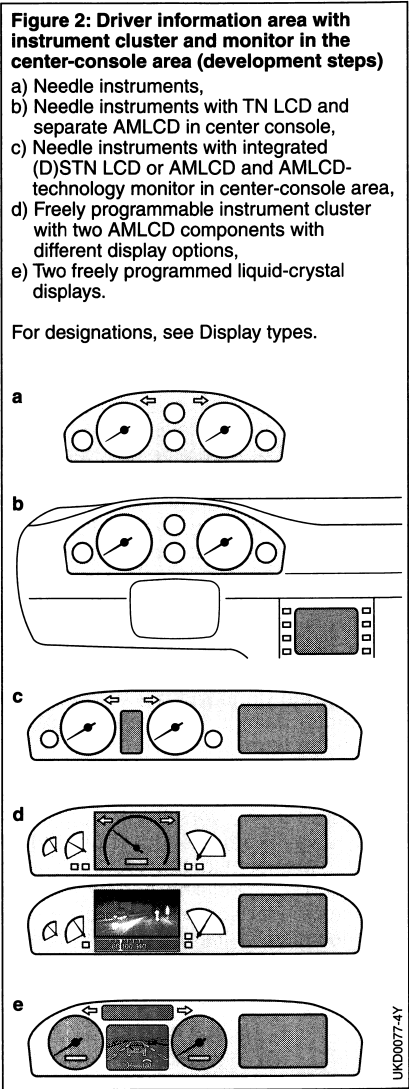
The supply of available information and the necessary, advisable or desirable information for the respective occupant determine which communication areas are used in the case. Dynamic information (e.g. driving speed) and monitoring information (e.g. fuel level), to which the driver should respond, is displayed in the instrument cluster in a favorable reading position close to the driver's primary field of vision.

A head-up display (HUD), which reflects the information on the windshield, is ideally suited to engaging the driver's attention (e.g. in the case of warnings from a driver-assistance system or for route directions). The head-up display is also suitable for displaying the speed in a digital form. A supplementary feature is the output of acoustic signals or speech.

Status information or more extensive operation dialogs (e.g. for vehicle navigation) are preferably shown in the central display in the center console. The operating units are usually assigned to this central display for more compact vehicles. For more spacious vehicles with a high-mounted central display (see Figures 2c and 2d), the preferred place to arrange the control units is in the primary reach area in the form of a rotary/push control element on the transmission hump.

Information of an entertainment nature is featured in the vehicle rear compartment, away from the primary field of vision. This is also the ideal location for a mobile office. The backrest of the front-passenger seat is a suitable installation location for the monitor and operator unit of a laptop computer.

“Dual View” or “Split View” displays for the center console have additionally been available since 2009; these displays can show different information to driver and passenger so that the passenger can, for example, watch videos without distracting the driver while the driver sees the navigation-system information.

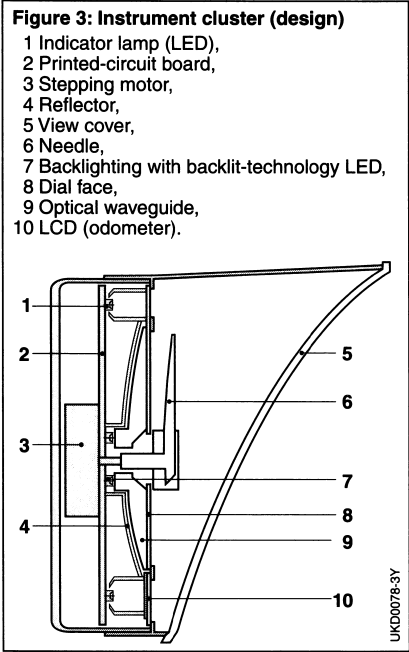


Instrument clusters

Earlier single instruments for the optical output of information (e.g. driving speed, engine rpm, fuel level, and engine temperature) were initially superseded by more cost-effective, well-lit and antireflective instrument clusters (combination of several information units in one housing). The passage of time, with the continual increase in information, saw the creation of the modern instrument cluster in the existing space available, with several needle instruments and numerous indicator lamps (Figure 2a). This first generation of instrument cluster was dominated by the eddy-current measuring instrument for the speedometer, the moving-coil measuring instrument for the rev counter, and the hot-wire instrument for the fuel level.

Measuring instruments

Even today most instruments still operate with mechanical needles and dial faces (Figures 2a to 2c). Initially moving permanent-magnet ratiometer elements



replaced the voluminous, mechanically driven eddy-current measurement instruments. Today stepping motors with low overall depth and high torque are predominant. Due to a compact magnetic circuit and (mostly) two-stage gearing with power consumption of only approx. 100 mW, these motors permit swift and highly accurate needle positioning (Figure 3).

Digital displays

The digital instruments fitted up to the 1990s (e.g. for indicating driving speed) displayed information using vacuum-fluorescence display (VFD) technology and, later, liquid-crystal (LCD) technology, but they have now largely disappeared in Europe. This unfortunately means that the advantage of a demonstrably fast and accurate speed reading has been lost. Today's Formula 1 cars all have digital speedometers.

Digital displays in instrument clusters can be found today in Japan (e.g. Toyota Prius) and in luxury-class cars in the USA.

Lighting

To illuminate instrument clusters, backlighting technology has, on account of its attractive appearance, gained acceptance to a large extent over the frontlighting technology used previously. Bulbs have been replaced by long-lasting light-emitting diodes (LEDs). LEDs are suitable both as warning lamps and as backlighting for scales, displays and needles (using plastic optical waveguides if necessary).

Where for a long time only monochrome LEDs in the colors yellow, orange and red were available, now blue and highly efficient white LEDs are available.

Color LCDs, on account of their very low transmission (typically approx. 6%), had initially required cold cathode fluorescent lamps (CCFLs) for the backlighting in order to achieve a good contrast in daylight. These have in the meantime been replaced by highly efficient white LEDs.

Graphics modules in the instrument area

Fitting vehicles with a driver's airbag and power-assisted steering as standard has resulted in a reduction in the view through the top half of the steering wheel. At the same time the amount of information that has to be displayed in the installation space available has increased. Prior to the availability of graphics displays whose display surfaces can show any information – flexibly and ordered by priority – engineers tried to solve this installation dilemma initially using additional displays which were positioned on the dashboard – e.g. trip computers and the first monitors for displaying navigation information, which were sometimes also mounted on a gooseneck. The availability of graphics monitors resulted in the hybrid instrument with classic needle instruments and a graphics module (Figure 2c).

The graphics module in the instrument cluster mainly enables an indication of driver-related functions such as, for example, service intervals, check functions covering the vehicle's operating state, as well as vehicle diagnostics as needed by a workshop. They can naturally also show route-direction information from the navigation system, where, due to the small surface area of these modules, digitized map excerpts must be missed out so that only route-direction symbols such as turnoff instructions or intersection symbols appear in the display. This limitation has also been retained in newer vehicles. The initially monochrome modules were quickly followed in higher-specification vehicles by color displays which can be read more quickly and accurately because of their color resolution.

Since 2005 active-matrix displays (see below) have also been in use to represent analog instruments (Figure 2d). One example is the instrumentation in the Mercedes S-Class, in which the speed indication is emulated using an LCD monitor. During changeover to the night-vision function (see Night-vision system) the camera's conditioned video image appears, while the engine rpm indication is shown in bar form under the video image.

With the launch of the Mercedes S-Class in model year 2013 the instrument cluster was replaced for the first time by a full-screen liquid-crystal monitor. Such a freely programmable instrument offers many benefits. Either the information can be arranged according to customer preference (e.g. at the end of the line) in the display or drivers who are familiar with digital media can program their instrument clusters themselves. This option is offered in the Chevrolet Corvette C7.

In view of the drop in prices of these displays it can be assumed that the digital display in the instrument cluster will become widely accepted because in this way the variety of versions of entire vehicle model series can be reduced to a single, flexibly programmable unit, resulting in huge logistical savings.

The introduction of the graphics monitor as the instrument cluster was also accompanied by a growth in the format of the center-console display.

Central display and operating unit in the center-console area

The arrival of driver-information systems, initially mainly navigation and telephone, saw the establishment of a further monitor with accompanying operating elements in the center console (Figure 2). It was initially positioned here because it was possible here to create sufficient installation space with the installation bay for the car radio and the ashtray. The operating elements were arranged along the edges of the display (Figure 2b). The vehicle manufacturers have since switched to the ergonomically more favorable solution of installing the monitor in the center-console area at the height of the instrument cluster (Figure 2c). In this connection, most German automobile manufacturers have replaced the button input on the monitor edge with a combined rotary/push input button in the driver's primary area of reach on the center console. Operation directly via the display is possible with touch screens.

A wealth of information is shown on this central monitor, e.g. navigation, communication (telephone, SMS, Internet), audio (radio, digital sound recording media), video and TV when the vehicle is stationary, climate control, and settings (date, time). Information from the new driver-assistance systems (e.g. parking and maneuvering aids) can also be usefully displayed here.

The important issue for all visual displays is that they can be easily read within the driver's primary field of vision or its immediate vicinity so as to ensure that the driver does not have to look away from the road for long periods. Positioning this terminal, which is of universal use to driver and passenger, in the upper center-console area is effective and necessary from both ergonomic and technical standpoints. The demands placed by TV reproduction and the navigation system on the video and map display determine the demands placed on the resolution and the color reproduction of the monitor.

For this central display monitor, there has initially been a change from a small 6" monitor with a 4:3 aspect ratio to a wider format with a 16:9 aspect ratio, which allows additional route-direction symbols to be displayed as well as the map. Newer vehicles with the central monitor located in the upper center-console area sometimes have, due to the greater space available, much larger monitor formats. The Tesla Model S even uses a vertically arranged monitor with a diagonal of 17" as a combined display and operating unit in the center console.

Display types

Liquid-crystal display

The most display most commonly used today in vehicles is the liquid-crystal display (LCD). Being a passive display which emits no light itself but modulates incident light, it requires additional lighting.

Twisted Nematic LCD

TN LCD (Twisted Nematic Liquid-Crystal Display) is the most commonly used form of display. The name derives from the arrangement internally of rectangular molecules twisted through 90° at zero voltage. This causes the polarization plane of the light passing through the cell to rotate through 90° (Figure 4). If this cell is arranged between crossed polarizers, it is transparent in the de-energized (zero-voltage) state. When a voltage is applied, the molecules are rotated in the field direction (Figure 4, middle segment). The cell becomes non-transparent, i.e. it is a light valve.

The operating range is -40 to 125°C . The switching times are slightly longer at low temperatures due to the viscous properties of the liquid-crystal material.

Depending on the choice of polarization direction of the externally applied polarizer film, the TN LCD can be operated in positive contrast (dark characters on a light background) or negative contrast (light characters on a dark background).

The TN LCD is usually operated in negative contrast in the vehicle since this comes close to the familiar appearance of printed dials. Negative-contrast cells always required backlighting.

Separately controlled segment areas can be used to portray numbers, letters, and symbols. TN technology is suitable not only for smaller display modules but also for larger display areas and modular LCD instrument clusters such as the instrument cluster in the Audi Quattro model year 1984.

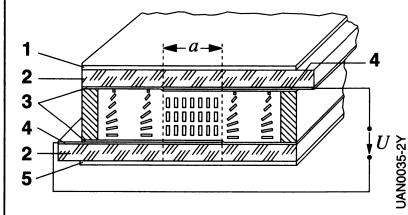
Active-matrix LCD

Dot matrix displays with graphics capabilities are needed to display infinitely variable information. The task of the visually sophisticated and rapidly changing display of complex information in the area of the instrument cluster and the center console with high-resolution liquid-crystal monitors with video capabilities can only be performed effectively by an active-matrix liquid LCD (AMLCD). The pixels are addressed with thin-film field-effect film transistors (TFT LCD, Thin-Film Transistor LCD). Display monitors with diagonals of 3.5 to 10 inches in the center-console area and an extended temperature range (-25 to 110°C) are available for motor vehicles and are the most widely used monitor technology in vehicles today. Formats of 10 inches and more are used for the freely programmable instrument cluster.

AMLCDs (Figure 5) consist of the "active" glass substrate with the semiconductor structures and the opposing plate with the color-filter structures. The active substrate accommodates the pixel electrodes made from indium tin oxide, the metallic row and column conductors, and semiconductor structures. At each intersecting point of the row and column conductors, there is a thin-film field-effect transistor, which is etched in several masking steps from a previously applied sequence of layers. A capacitor is generated at each pixel as well.

Figure 4: Principle of operation of a liquid-crystal display (nematic cell)

- 1 Polarizer, 2 Glass,
 - 3 Orientation and insulation layer,
 - 4 Electrode, 5 Polarizer.
- a* Segment area.



The opposite glass plate accommodates the color filters and a “black matrix” structure for covering the metallic row and column conductors, which improves display contrast. These structures are applied to the glass in a sequence of photolithographic processes. A continuous counter-electrode is applied on top of them for all the pixels. The color filters are applied

either in the form of continuous strips (good reproduction of graphics information) or as mosaic filters (especially suitable for video pictures).

Organic light-emitting diodes

The luminescence excitation for organic, electroluminescent display units (OLED, organic light-emitting diode) occurs, as in light-emitting diodes (LEDs), through injected charge carriers, but here in a layer of organic materials. Three processes have to take place within the system of coatings for electroluminescence to occur: Injection, transportation of both types of charge carriers (electrons, holes) through the layer as well as their recombination.

The organic layers are embedded between two electrodes. Figure 6 shows the basic structure of an OLED picture element. Glass (or plastic foil) coated with indium tin oxide (ITO) is typically used as the anode; this lets the generated light through (downwards in the graphic). The cathode is made of metal. The organic material is located between them. Charge carriers are injected into the material using the electric contact points by applying a voltage. These are moved toward each other by the polymer layer. When charge carriers of different charges meet (electrons and holes), this causes the radiative recombination as described above (see also OLED, electronics).

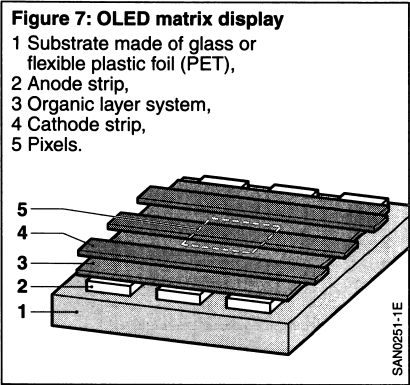
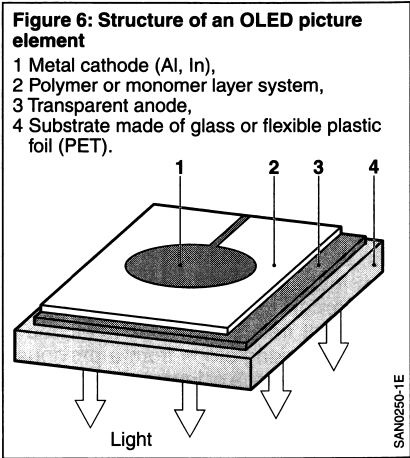
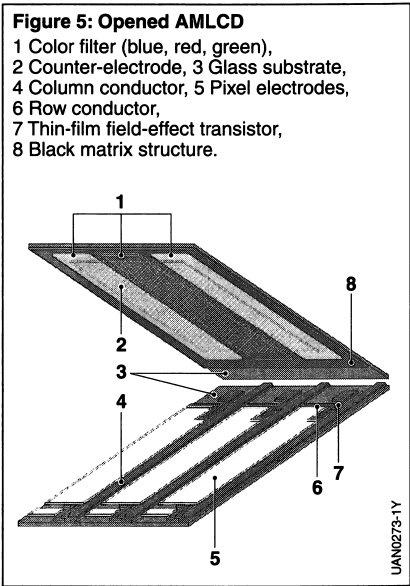


Figure 7 shows the structure of an OLED matrix display. The organic layer is located between the row and column electrodes arranged perpendicularly to each other. Multi-color reproduction is achieved by OLED materials in a dot matrix that emit different colors.

OLED displays have already been established in the consumer area (e.g. mobile phones) for years. Due to the high requirements for resistance to climatic conditions, OLEDs have only been used for small, monochrome, alphanumeric and simple graphic displays to date, e.g. for displaying air-conditioner functions. The option to construct OLEDs with curved surfaces using plastic substrates could attract interest in the future from the standpoint of providing good anti-reflection conditions in a vehicle.

Head-up display

Conventional instrument clusters are situated at a viewing distance of 0.8 to 1.2 m. In order to read information in the area of the instrument cluster, the driver must adjust his or her eyes from long distance (observing the road scene) to the short viewing distance for the instrument. This accustomization process usually requires, depending on the driver's age, 0.3 to 0.5 s.

Head-up displays (HUDs) were first used in military-aviation applications. For motor-vehicle applications they were available in a simple design, usually as a digital speedometer, in parallel with the

analog speedometer in Japan and in the USA as an optional extra. An improved form was initially used in the USA and later also in European vehicles.

The image of a head-up display is projected with the aid of the windshield into the driver's primary field of vision. The optical system generates a virtual image at such a viewing distance that the human eye can remain adjusted to long distance. Head-up displays do not require the driver to divert their eyes from the road – thus allowing the driver to register at all times safety-critical driving situations without being distracted. The driver does not need to look at the instrument cluster when important information is shown in the headup display.

Body

A typical head-up display (Figure 8) features an activated display module for generating the image, a lighting facility, an optical imaging unit, and a combiner, which reflects the image to the driver's eyes. In a motor vehicle it is usually the windshield which acts as the combiner. To avoid double images – caused by reflections on the inner and outer boundary surfaces – the windshield is slightly wedge-shaped in design. From the driver's perspective the two images created at the boundary surfaces then coincide.

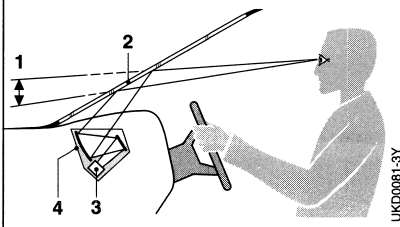
A real image is created in the display module. This module can be a display or a back-projection onto a diffusing surface, e.g. with a scanning laser beam. This real image is only roughly 20×40 mm in size, but the luminance required for good readability in daylight is more than $50,000 \text{ cd/m}^2$, i.e. 100 times more than a conventional direct-view display. This image is reflected through the windshield into the driver's eyes. For the driver this virtual image of the driving situation in front of the vehicle is superimposed.

Optical elements (lenses, concentrating reflectors) are generally inserted into the beam path to increase the virtual distance of the image.

Particularly high-contrast segment TN LCDs can be used as the display for monochrome head-up displays with

Figure 8: Head-up display (principle)

- 1 Virtual image,
- 2 Reflection in the windshield,
- 3 Display module: liquid-crystal display (LCD) with backlighting,
- 4 Optical system.



modest levels of information content. More sophisticated, multicolor displays use polysilicon-technology AMLCDs.

Display of information of head-up displays

The virtual image should not cover and obscure the road scene ahead; it is therefore displayed in an area with low information content, in other words “floating above the hood” (Figure 9). In order to prevent the driver from being overwhelmed with stimuli in his or her primary field of vision, the head-up display should not be overloaded with information, and is therefore never a practical substitute for the conventional instrument cluster. It is, however, particularly well suited for displaying navigation notices (arrows) and safety-related information such as warnings or information from the ACC system (Adaptive Cruise Control, see Adaptive cruise control system).

Because of the beneficial display of information, it can be assumed that the number of headup displays worldwide will increase dramatically.

Augmented-reality headup display

“Augmented-reality” head-up displays offer an even greater benefit than showing information in the headup display without local reference to the environment. They require a greater level of technical sophistication in realizing the projection

unit by using a laser or a DLP module to generate the image. DLP stands for “Digital Light Projection”, the generation of images by micromechanical elements, as are also used in projectors.

Augmented-reality head-up displays are characterized by a larger projection field. This enables the system to display the warning of an obstacle in the driver’s field of vision and at the virtual distance in which it is located in nature. To enable the information to be read without parallax, however, a position correction depending on the position of the driver’s head is required. Series launch in premium vehicles is announced for 2019.

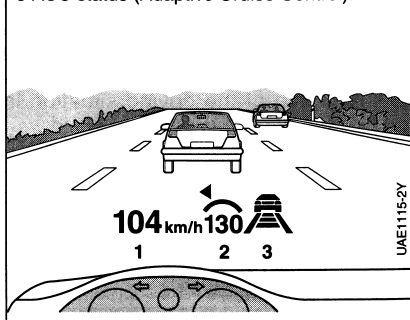
With this system, route-direction information can be displayed for example at an intersection precisely where the junction suggested by the navigation system is situated; at an expressway/interstate exit the arrow for recommending the exit can be positioned on the deceleration lane.

References

- [1] M. Wheeler: HUD Systems: Augmented Reality is coming to your windshield. Photonics Spectra 02/2016.

Figure 9: Information shown in the head-up display

- 1 Present speed,
- 2 Desired speed,
- 3 ACC status (Adaptive Cruise Control).



Radio and TV reception in motor vehicles

Wireless signal transmission

Wireless transmission technology permits the simultaneous broadcasting of information to large populations. It is also of major significance to mobile radio reception as used in motor vehicles. At present, the importance of digital transmission methods is growing. The wireless section of the transmission chain also uses analog signal transmission, so the two technologies are basically identical.

Radio and TV broadcasting

Wireless radio and TV broadcasting is primarily used for terrestrial transmissions. In the case of analog radio broadcasting, the audio signal is modulated on the high-frequency signal. In the receiver, the received high-frequency signal is then converted to the baseband frequency and demodulated. The final signal obtained in this way is identical to the useful signal.

In telecommunications, the propagation of an electromagnetic wave is used to transmit information whereby the amplitude, the phase or the frequency of this oscillation is altered depending on the information to be transmitted. The customary frequencies range from a few kilohertz up to 100 GHz. Some of the commonly used frequency ranges are

set out in Table 1. The use of frequency bands is subject to legal control (Telecommunications Act for Germany, 2004). Each country's frequency allocation plan is based on international agreements that are set out in Article S5 of the Radio Regulations of the ITU (International Telecommunication Union, [1]).

Information transmission using highfrequency waves

The variation in a high-frequency signal used to transmit a useful signal from a transmitter to a receiver is called modulation. The modulated high-frequency signal is emitted within a precisely determined, narrowly defined frequency band by an antenna. The receiver selects precisely that frequency band from the large number of frequencies received by the antenna. In this way, wave propagation between transmitter and receiver is a link within the signal transmission chain.

For example, when it comes to the transmission of an audio signal, the useful signal in contrast to the high-frequency carrier signal is made up of various frequencies ranging up to a maximum of 20 kHz. The high-frequency carrier is modulated with this low-frequency signal. A transmitter antenna beams out the carrier wave.

Table 1: Overview of some frequency bands in radio and TV broadcasting

Wavebands	Wavelengths λ in m	Frequencies f in MHz	Examples
Long wave (LW)	$\approx 2,000 - \approx 1,000$	0.148 – 0.283	Analog radio broadcasting
Medium wave (MW)	$\approx 1,000 - \approx 100$	0.526 – 1.606	Digital Radio Mondiale (DRM)
Short wave (SW)	$\approx 100 - \approx 10$	3.950 – 26.10	
Very high frequency (VHF)	$\approx 10 - \approx 1$	30 – 300	
Band 1		47 – 68	TV
Band 2		87.5 – 108	Digital Audio Broadcasting (DAB)
Band 3		174 – 223	
Ultra high frequency (UHF)	$\approx 1 - \approx 0.1$	300 – 3,000	
Band 4		470 – 582	TV
Band 5		610 – 790	Digital Video Broadcasting (DVB-T2), Digital Video Broadcasting (DVB-H)
L-band		1,453 – 1,491	Digital Audio Broadcasting (DAB)
Super high frequency (SHF)	$\approx 0.1 - \approx 0.01$	3,000 – 30,000	
		10,700 – 12,750	Digital Video Broadcasting (DVB-S)

The maximum distance at which the signal can still be received and the reception quality depend on the frequency, among other things. Short-wave and long-wave have very long ranges, in some cases intercontinental, whereas the reception range of VHF transmissions is hardly any further than the line of sight.

The receiver station demodulates the signal. The resulting low-frequency electrical oscillation is then converted by a loudspeaker into acoustic oscillations.

Amplitude modulation

Amplitude modulation (AM) is the change in amplitude A_H of the high-frequency oscillation at frequency f_H in synchronization with the low-frequency oscillation (A_N, f_N) (Figure 1).

Amplitude modulation is used in the short-wave, medium-wave and long-wave bands, for example.

Frequency modulation

Frequency modulation (FM) is the change in frequency f_H of the high-frequency oscillation in synchronization with the low-frequency oscillation (Figure 2).

Frequency modulation is used for FM radio and the sound channel of analog TV transmissions, for example. The transmissions of frequency-modulated signals are impaired by amplitude-modulation interference (e.g. caused by the ignition systems of spark-ignition engines) to a lesser degree than the transmissions of amplitude-modulation transmitters.

Digital modulation processes

In the case of digital modulation processes, the amplitude or the frequency of the carrier is discretely altered. One or more bits can thus be allocated to each of these carrier states so as to enable digital information to be transmitted.

Reception problems

VHF signals have virtually a linear propagation. As a result, a car radio may lose the signal from a VHF transmitter that is only 30 km away if there is high ground between the car and the transmitter. On the other hand, reception may be unimpaired at a location further away if there is a clear "line of sight" between the car and the transmitter. Such "radio shadows" are thus often covered by a fill-in transmitter.

Signals may be reflected off the sides of valleys or high-rise buildings. The reflected signals then arrive at the receiving antenna with a time delay and are superimposed on the signals received directly from the transmitter. This produces what is known as "multi-channel reception". It causes multipath interference and results in the deterioration of sound quality in radio reception.

Propagation of electromagnetic waves is impaired by conductors within the transmitter's radiation field (e.g. steel masts or power lines) and even nearby forests, houses, or locations in deep valleys. The characteristics of wave propagation are important when it comes to suppressing interference in motor vehi-

Figure 1: Amplitude modulation (AM)

- a) Low-frequency oscillation at amplitude A_N and frequency f_N .
- b) Unmodulated high-frequency oscillation,
- c) Modulated high-frequency oscillation.

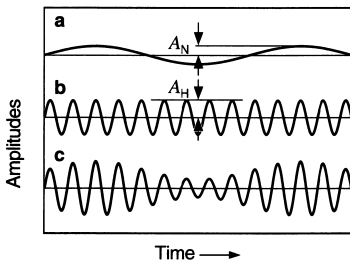
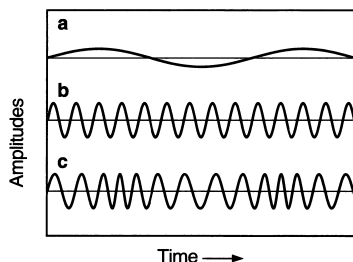


Figure 2: Frequency modulation (FM)

- a) Low-frequency oscillation at amplitude A_N and frequency f_N .
- b) Unmodulated high-frequency oscillation,
- c) Modulated high-frequency oscillation.



cles effectively. Interference-free reception is impossible if the signals received from the transmitter are too weak. Thus, reception of a previously perfectly interference-free signal will break down suddenly when a car enters a tunnel, for example. This can be explained by the shielding effect of the reinforced-concrete tunnel walls which reduce the useful field strength of the transmitter signal to which the radio is tuned. At the same time, the interference-field strength remains the same. Under certain conditions, it may not be possible at all to continue to receive the radio-station signal. Similar phenomena can also be experienced when traveling in mountains, for example.

Radio interference

Radio interference is caused by undesirable high-frequency waves which are directed together with the desired signal to the receiver. It occurs wherever electrical currents are suddenly interrupted or switched on. High-frequency interference waves are thus produced, for example, by the ignition of a spark-ignition engine, the actuation of a switch, or the switching operations on the commutator of an electric motor. Such rapid changes of current generate high-frequency waves which interfere with radio reception by receivers located close by. The effect of the interference depends on the steepness of the signal pulse and its amplitude, among other things.

Radio interference caused by such steeply rising current pulses can be reduced or completely eliminated by EMC measures (electromagnetic compatibility).

Interference can travel to the receiver in different ways: directly through wires connecting the interference source and the receiver, or by wireless transmission of electromagnetic radiation, or by capacitive or inductive coupling. Strictly speaking, the last three options cannot be separated from one another.

Signal-to-noise ratio

Reception quality depends on the strength of the electromagnetic field generated by the transmitter. This should be substantially greater than the strength of the interference field, i.e. the ratio be-

tween the strength of the transmitter signal and the strength of the interference field – the signal-to-noise ratio – should be as large as possible.

A receiver close to the interference source receives not only the useful signal from the desired transmitter, but also the undesired interference signal, if it is transmitted at the same frequency. Nevertheless, good-quality reception is still possible provided that the field strength of the desired transmitter signal at the point of reception is very high in comparison with the strength of the electromagnetic field generated by the interference source. The useful field strength of the signal from the transmitter depends on transmitter power, transmitter frequency, the distance between the transmitter and the receiver, and the propagation characteristics of the electromagnetic waves. In the case of medium-wave and long-wave signals, the field strength of the transmitter signal can be weakened by difficult topology to such an extent that the signals of even powerful transmitters have low useful field strengths at some reception locations. VHF signals may be subject to heavy fluctuations in useful field strength under certain conditions. Receivers in motor vehicles may also suffer from relatively low useful voltages at the receiver input due to the short effective height of the antenna. Accordingly, the opportunities for improving the signal-to-noise ratio in the receiver are very limited.

By optimizing antenna positioning, the available useful voltage at the receiver input can be increased, thereby improving the signal-to-noise ratio, which is the decisive factor in reception quality. Frequently, however, a compromise is made between design considerations and technical demands. Another means of improving signal-to-noise ratio is by reducing the strength of the radiated interference signals.

Receiver design also has an impact on reception quality. In addition to metallic shielding, which prevents the direct entry of radiated interference, and filters on the power source input, some receivers have circuits fitted with automatic interference suppression (see section entitled "Reception improvement").

Radio tuners

Radio tuners in motor vehicles are frequently called car radios or automotive sound systems. However, this term refers not only to a radio tuner but also to devices with a large number of integrated information and entertainment functions. These include, for instance, the analysis of supplementary information (e.g. traffic news), players for reproducing from storage media (e.g. CDs and SD cards), as well as integrated radio communication interfaces, cellular phones and other devices.

In the past few years, conventional analog transmission technology has developed new systems. For this reason, modern car tuners are capable of receiving a wide variety of radio broadcast systems worldwide. As well as conventional radio broadcasting, these systems include among others DAB (Digital Audio Broadcasting), DRM (Digital Radio Mondiale) and SDARS (Satellite Digital Audio Radio Services).

The conventional radio tuner is designed to receive analog FM and AM modulation and has an analog signal path from the

antenna to the audio signal. Modern car tuners with the highest received power, on the other hand, process signals digitally. The IF signal (intermediate frequency) supplied by the tuner is digitized by an analog-digital converter, and then processed. In standards covering digital modulation essentially only demodulation in the digital part of the signal path changes.

Conventional tuners

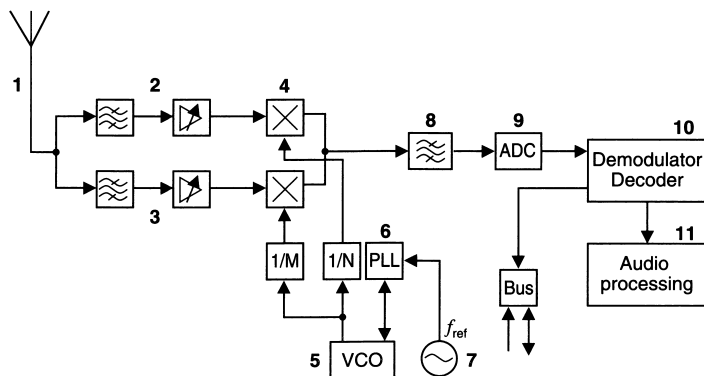
Signal processing

The antenna, which is predominantly designed as a rod or window antenna, picks up the electromagnetic signal emitted by the transmitter. This consists of different channels with a fixed frequency spacing. The high-frequency alternating voltage generated at the base of the antenna is routed to the receiver and processed there.

The conventional tuner for analog radio reception basically contains two signal paths: one for processing amplitude-modulated signals and one for processing frequency-modulated signals. These are

Figure 3: Block diagram of a radio tuner

- 1 Antenna, 2 FM input stage, 3 AM input stage,
 - 4 Mixer stage, 5 Voltage-controlled oscillator (VCO),
 - 6 Phase-locked loop (PLL), 7 Reference-frequency oscillator,
 - 8 Intermediate-frequency filter (IF), 9 Analog-digital converter,
 - 10 Demodulator and decoder, 11 Audio processing.
- f_{ref} Reference frequency.



usually divided into the blocks described in the following (Figure 3).

AM input stage

A bandpass filter limits the amplitude-modulated signal in the LW, MW and SW bands, and the resulting signal is amplified in the following stage with low noise.

FM input stage

The frequency-modulated VHF signal is received by a separate input stage. The input filter is either tuned to the frequency to be received or configured to the entire received band. The received-signal level is then adjusted to the desired input level for the following mixer stage with low noise by an automatically controlled amplifier.

Voltage-controlled oscillator

The oscillator (VCO, voltage-controlled oscillator), whose frequency is controlled by a phase-locked loop (PLL), generates a high-frequency oscillation which is subdivided. The input signal is converted with the aid of this signal into a constant intermediate frequency (IF) in the mixer stage. A quartz-stabilized signal serves as reference frequency.

Mixer stage

The mixer stage converts the input signal into a constant intermediate frequency. Different mixer stages are frequently used for receiving FM and AM signals. On the other hand, the principle of frequency conversion is the same.

IF filter and amplifier

The IF signal recovered in this way is then fed to an IF filter and a controlled amplifier.

Analog-digital converter (ADC)

The analog-digital converter (ADC) converts the analog IF signal into a digital signal.

Demodulator

The demodulator generates the digital audio signal from the digital IF signal.

Decoder

Additional information, such as RDS data (Radio Data System), is decoded by the decoder and passed on to a processor for processing.

Audio processing

After demodulation, the audio signal may be adapted, for example, to the vehicle conditions and the listener's preferences. This can be achieved by using the appropriate controls to adjust tone and volume or to vary the level between front and rear or between left and right.

Digital receivers

A digital receiver (ADR, advanced digital receiver) is a highly integrated receiver module whose input signal is the analog or digital IF signal. The analog signal is converted into a digital signal, the digital signal is processed on the digital level. This technology allows a type of signal processing that would not be possible using analog technology. It generates, for example, IF filters which provide for exceptionally good harmonic-distortion levels, and whose bandwidth is variable and can be adapted to the reception conditions. In addition, there is a larger number of other means of processing the received signal in such a way as to substantially reduce interference in the audio signal (see SHARX, DDA and DDS).

Digital equalizer

The digital equalizer (DEQ) consists of a multiband parametric equalizer which provides separate adjustment features for the mid-frequency, and the amplification/attenuation of individual filters. The suppression of unwanted resonances thus obtained optimizes sound quality inside the vehicle. The frequency response of the speakers can also be linearized.

Preset equalizer filters can also be implemented in some devices. These can be activated according to music genre or vehicle type (e.g. jazz or pop, van or sedan).

Digital Sound Adjustment

"Digital Sound Adjustment" (DSA) is a system which automatically analyzes and corrects frequency response in in-car systems. A microphone and a digital signal processor (DSP) are used to pick up and analyze a test signal generated by the speakers. The optimum sound curve for the vehicle is then set on the equalizer.

Dynamic Noise Covering

While the vehicle is in motion, the "Dynamic Noise Covering" (DNC) function uses a microphone to constantly detect and analyze the vehicle-noise spectrum that is blocking out the audio signal and impairing the perceived sound quality. The function uses selective amplification or selective dynamic compression (reduction of dynamic response between minimum and maximum values) of the interference frequencies to maintain optimum reproduction of sound quality, regardless of driving noise.

Reception quality

Analog radio broadcasting is primarily used for terrestrial transmissions. The transmission path is not always ideal, with the result that reception quality may be impaired, depending on the transmitter/receiver constellation and environmental conditions. In the case of VHF reception, reception locations may be critical because of the transmission-path problems described below.

Fading

Fading is caused by fluctuations in signal reception level due to obstacles in the signal path, such as tunnels, high-rise buildings, or mountains.

Multipath reception

Multipath reception is caused by the reflection of signals off buildings, trees or water. This can easily lead to a substantial dip in reception field strength, and even total signal loss. The differences in the strength of the received signal field strength occur within a few centimeters of each other. Such fluctuation has a particularly detrimental effect on mobile receivers, such as car tuners.

Adjacent-channel interference

Adjacent-channel interference occurs when there is another channel received with a high field strength close to the channel received.

High-level signal interference

High-level signal interference occurs close to the transmitter at high field strength. The receiver protects its input by reducing the field strength. This has the effect of attenuating the weaker signals from other transmitters, i.e. they become quieter.

Overmodulation

Some transmitters increase the modulation level in order to achieve a greater range or higher loudness level. The disadvantages of this process are greater distortion factor and greater susceptibility to multipath interference.

Ignition interference

High-frequency interference sources (such as the ignition of a spark-ignition engine, the operation of a switch, or switching operations on the commutators of electric motors) produce reception interference.

Reception improvement

A large number of functions for improving received power are implemented in modern automotive sound systems. An overview of the most important functions is provided in the following.

Radio Data System

Radio Data System (RDS) is a digital data transmission system for FM radio. This format is standardized throughout Europe. It provides the tuner with extra information in addition to the desired audio signal by using alternative received frequencies with the same modulation. This enables, for example, the tuner to switch continuously to the frequency with the least interference. Table 2 provides an overview of the information transmitted.

Table 2: RDS codes

Code	Information transmitted
PS	Name of the station received
AF	List of alternative frequencies on which the station also broadcasts
PI	Identifies the broadcast station
TP, TA	Traffic-program station identification, traffic-announcement identification
PTY	Identification of the station type
EON	Signals traffic announcements on a parallel station
TMC	Standardized traffic information
CT	Time (for synchronizing the clock in the vehicle)
RT	Text transmission (e.g. title of music track)

Digital Directional Antenna

The “Digital Directional Antenna” (DDA) system developed by Bosch uses the signals from two antennas to calculate a synthetic antenna with a new directional characteristic. This permits suppression of interference caused by multipath reception as shown in Figure 4.

Digital Diversity System

The reception characteristics of FM radio are heavily dependent on location. A Digital Diversity System (DDS) has a number of antennas at its disposal so

that it can switch between them in order to enhance reception. The Digital Diversity System integrated in the digital receiver uses exactly the same signal for its switching strategy and the signal is available as the audio signal after demodulation.

High-cut

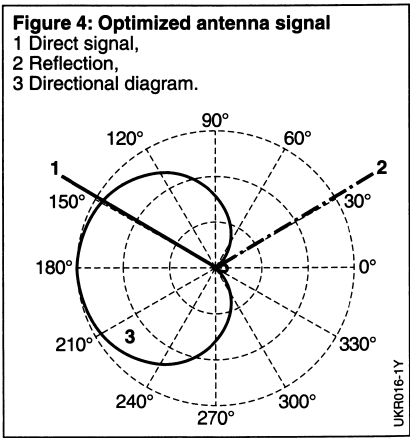
Interference caused by such effects as fading and multipath reception has a greater effect on higher audio frequencies. For this reason, modern automotive sound systems have a facility for detecting such interference and reducing the level of the audio signal at higher audio frequencies when there is interference.

SHARX

SHARX is a function which automatically adjusts the bandwidth of the intermediate-frequency filter for FM reception to suit reception conditions. If different stations transmit at frequencies that are very close to one another, this function significantly increases the clarity of separation by reducing the bandwidth and allows virtually interference-free reception. If there are no adjacent channels, the bandwidth can be increased and thus harmonic distortion reduced.

Automatic interference suppression

A further measure for improving reception is automatic interference suppression, which suppresses interference signals generated by interference sources from both the present vehicle and other vehicles. To this end, the demodulated signal, which contains interference pulses, as well as the useful signal, is blanked for that moment of interference and the gap created is filled.



References

[1] Radio Regulations. International Telecommunication Union (ITU).

Traffic telematics

Transmission paths

Traffic telematics refers to systems that transmit traffic-related information to and from vehicles and, generally, which analyze this information automatically. Both unidirectional broadcasting (radio) and bidirectional mobile communications connections are available as transmission paths. Analog and digital radio provides only the path into the vehicle, with the information received identical for all receivers. Mobile communications connections on the other hand enable messages to be specifically received by way of individual requests and thus information to be exchanged between a vehicle and appropriate service providers in both directions.

The transmission paths also differ in the bandwidth limiting the information volume that is available and the transmission costs. The available bandwidth in mobile communications has increased by several orders of magnitude with each generation in recent years through the developments of GPRS (General Packet Radio Service), UMTS (Universal Mobile Telecommunication System), and finally LTE (Long Term Evolution). While data transmission by radio does not involve additional costs for receiving sound radio, costs are generally incurred for the information volumes on the mobile communications channel in proportion to the data volume.

In the future communication with "roadside units" in accordance with the standard WLAN 802.11p (Wireless Local Area Network) will serve as a further transmission path providing a high bandwidth with no additional transmission costs.

Standardization

The standardization of message content is an important precondition to enable the evaluation of information from various sources by different on-board terminals.

RDS/TMC standard

The widespread RDS/TMC standard (Radio Data System/Traffic Message Channel) for FM radio comprises content regarding the type of traffic disruptions (e.g. traffic jam, full road block), the causes (e.g. accident, icy roads), the expected duration, as well as identification of the road sections concerned. A numeric coding for traffic junctions, expressway sections and geographic regions already exists in many countries. However, it limits the messages for the most part to the major roads (expressways and highways).

TPEG standard

It is now also possible, via the TPEG standard (Transport Protocol Experts Group), to transmit traffic forecasts and recommended alternative routes. A limitation by numeric, predefined junctions and road sections within the road network, as used in TMC, is no longer necessary when the AGORA-C standard is used. This standard allows messages for any road to be coded without transmitters and receivers having to use identical-version reference tables. However, because of the bandwidth required, transmission is only possible via digital channels.

Information recording

The benefit of traffic telematics is dependent on the quality of the messages and how up-to-date they are. There are different data sources for recording information about traffic flow. "Historical" data are additionally used so as also to offer – independently of current messages – the best possible route planning.

Local information

The first data sources for automatically determining the traffic situation were induction loops integrated in the road surfaces which can record the average speed and number of vehicles at individual road points and transmit the data to an evaluating control center. This form of recording was supplemented by the introduction of sensors on expressway bridges which also collect this information.

Area-wide information

In order to receive area-wide information instead of local measurements, newer approaches resort to floating-car data or floating-phone data. The basic idea is to infer traffic situations from the movement data of many cars or mobile phones.

Floating-car principle

In the case of the floating-car principle, the in-car navigation device transmits the car's position and speed by mobile communications to a control center, which then calculates the current traffic situation by statistically analyzing these data.

Floating-phone principle

In the case of the floating-phone principle, the movement patterns of mobile phones are analyzed. This principle exploits the fact that every mobile phone is constantly transmitting information on the current reception situation to its base station. Characteristic patterns can be derived from the changed messages which are accompanied by the mobile communication device's change of location. These patterns are then used to infer the position of the device. Statistical processes are used first to evaluate whether the devices in question are

moving devices in vehicles and then to infer the traffic situation from them.

Benefits of the floating processes

The two floating processes are used not only to detect the traffic disruption itself, but also to determine and forward reference values for the delay caused by the disruption.

The movement profiles of the vehicles can also be collected, assigned a time, and compressed. This practice produces so-called hydrographs which reproduce for individual road sections the average driving speeds depending on the day of the week and the time of the day. In this way, recurring traffic disruptions such as slow-moving traffic and regular rush-hour traffic jams are depicted. The vehicle-navigation system can use these hydrographs as "historical" data as a function of the current time to specify a route and journey time adapted to the expected situation.

Dynamic route guidance

Through the standardized coding of traffic messages, it is possible also to display these messages in the vehicle in comprehensible text form for the driver. Furthermore, the computers in route-guidance systems can determine on the basis of the standardized coding whether a better alternative route exists in the event of disruptions. The relevant messages are filtered out from those available using the vehicle location and, if necessary, its movement along a route. If the associated amount of time lost is communicated as well as the actual disruption, this time lost can also be included in the route computation. In the event of alternative route guidance, the driver is instructed that the route has been recalculated on account of traffic announcements received. Further route recommendations will follow in accordance with the new route (see Vehicle navigation).

Furthermore, subscription traffic services not only transmit the more serious traffic jams and disruptions, but also indicate for all higher road categories the

existence of restricted driving speeds identifiable from the floating data. Thus, for example, the traffic situation can be made transparent by a color-coded, high-detail display of the traffic flows in the vehicle navigation's map display even when route guidance is inactive.

Vehicle-vehicle communication

Vehicle-vehicle communication is currently being tested as the logical next step in traffic telematics. The ultimate aim is to further increase road safety and to reduce economic losses due to traffic disruptions. A system of direct information transfer between vehicles can be used to send warnings about, for example, broken-down vehicles, approaching emergency vehicles, the location of the tail end of a jam, right through to relevant individual maneuvers such as hard braking. This gives the driver in the receiving vehicle time to react in a suitable way to the present situation.

The standard WLAN 802.11p (Wireless Local Area Network) serves as the basis for direct vehicle-vehicle communication. The basic principle behind the warning functions is the timely and correct communication of precise location information between the transmitting vehicle and a receiving vehicle. This involves both the continuous transmission of movement messages and the additional transmission of an extra warning message when disruptions and events are detected. The process of regularly repeating or even passing on received messages to other vehicles ensures that all the affected vehicles can be reached.

To prepare for market launch, engineers are currently testing the functionality and efficacy of the systems under everyday conditions in a variety of field tests conducted in for example Germany and the USA.

Driver-assistance systems

Introduction – driver assistance

Driver-assistance systems in modern vehicles can basically be divided into the categories comfort/convenience systems and safety systems. Comfort/convenience systems relieve the driver in performing monotonous, repetitive driving tasks. Typical examples are automatic turn-signal resetting after turning or Adaptive Cruise Control (ACC). Safety systems, on the other hand, are intended to support the driver in critical driving situations so that an accident is avoided or its consequences are lessened. Typical examples are driving-dynamics control (Electronic Stability Control, ESC) and airbags. As the specified system categories increasingly interact in the face of the increasing level of system networking in vehicles and driver support by comfort/convenience systems is intended to provide increased safety (avoidance of critical situations already in advance), there is increasingly a flowing transition between comfort/convenience and safety systems. For further details, refer to the descriptions in the section “Comfort/convenience and safety systems”.

Critical driving situations

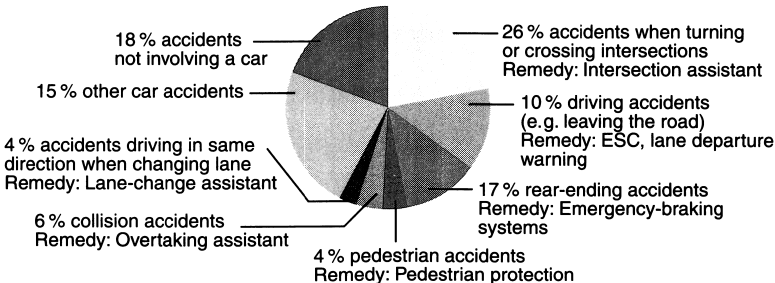
Driver-assistance systems aim to make the vehicle capable of perceiving its surroundings, interpret them, identify critical situations, and assist the driver in performing driving maneuvers. The aim is to identify critical situations early, i.e. already before they occur, and anticipate and defuse them, or at best to prevent accidents during critical situations or at worst to minimize as much as possible the consequences of an accident.

In critical driving situations, just fractions of a second are often decisive in determining whether an accident occurs or not. According to the study in [1], approximately 60 % of rear-end collisions and approximately 30 % of frontal impacts could have been avoided if the driver had reacted only half a second earlier. Every second accident at an intersection could be prevented by faster and correct driver reaction.

At the end of the 1980s, when the possibility of highly efficient and partially automated road traffic was presented as part of the EU “Prometheus” project, the electronic components for this task were not in existence. The highly sensitive sensors and powerful microcomputers now available have brought such vehi-

Figure 1: Operating areas of passenger-car safety functions in accidents involving personal injury by accident type

(Analysis of GIDAS accident database [2]).



cles driven by highly automated means a step nearer to realization.

The first driver-assistance systems which facilitate semi-automated vehicle guidance in specific traffic situations have been on the market since 2013 (e.g. traffic-jam assistant). Here the environment sensors scan the vehicle's surroundings and detect relevant objects. The driver-assistance systems follow a cascade of intervention and generate warnings or directly perform the maneuvers required (automatic steering or braking interventions). All this is done at those crucial fractions of a second faster, since a computer-controlled system can essentially react faster than a person.

Accident situation and actions

Accident research plays a significant role in the development of driver-assistance functions. Accident research at Bosch provides support among others in the design and development of new vehicle-safety functions while taking into account current traffic-accident occurrences. Assessments are conducted as to the effectiveness of these systems – i.e. of the potential for accident avoidance – and their effects on future accident occurrences.

To assess the effectiveness of passenger-car functions of driver assistance, an analysis of accidents involving personal injury was conducted for Germany on the basis of the accident database GIDAS (German In-Depth Accident Study [2]) (Figure 1). In Germany in 2015 there were 305,659 accidents involving personal injury, 82% of which involved a passenger car [3].

Around 26% of accidents involving personal injury in which a passenger car is involved occur during a turning or crossing maneuver. Here different intersection-assistant functions will be able in future to reduce accidents.

Every tenth accident involving personal injury (10%) can be put down to driver error; in many such cases involving passenger cars, accidents can already be avoided or the consequences of the accidents lessened with driving-dynamics control (ESC) and lane departure warning.

A further 17% of all accidents involving personal injury and passenger cars arise when one vehicle rams into another vehicle driving in the same direction. Collision-warning systems can counteract these accidents in an initial stage (e.g. Adaptive Cruise Control). In a further stage collision-avoidance systems prevent the accident by actively intervening in the driving dynamics, for example through brake intervention with the emergency-braking system (Automatic Emergency Braking, AEB).

Accidents involving unprotected road users such as pedestrians or cyclists demonstrate a high degree of complexity. The first emergency-braking pedestrian-protection functions for passenger cars are already available on the market. These operate in up to 4% of all accidents involving pedestrians. Research is currently being conducted into extending these pedestrian-protection systems to further reduce the occurrence or the consequences of such an accident by means of automatic avoidance maneuvers.

Collision accidents which usually occur during overtaking and can be positively influenced by overtaking-assistance systems amount to 6%. An additional reduction in accidents by 2% or in total 4% can be expected when the driver is supported when changing lanes by an assistance system.

In spite of the already high traffic-safety standards, according to the accident research conducted by Bosch up to 40% of accidents involving personal injury and passenger cars still do not involve the operation of a vehicle-safety system – accident research is helping here to develop further vehicle-safety functions or to advance their market acceptance.

Applications

Driver-assistance systems have a wide range of applications. They can be divided into active systems which intervene in the driving dynamics and into passive system with no intervention in the driving dynamics.

As already mentioned, a further distinction is made between comfort/convenience systems to reduce the burden on the driver (driver support) with the long-

term goal of fully automated driving and safety systems with the aim of accident avoidance or mitigation of accident consequences.

Comfort/convenience and safety systems

Figure 2 shows according to the selected system the range of driver-assistance systems and functions.

Passive safety functions

Passive safety functions (Figure 2, bottom left quadrant) contain the actions for mitigating the consequences of accidents such as airbag deployment and the functions for passive pedestrian protection (specific design of the front of the vehicle to mitigate the consequences of collisions with pedestrians).

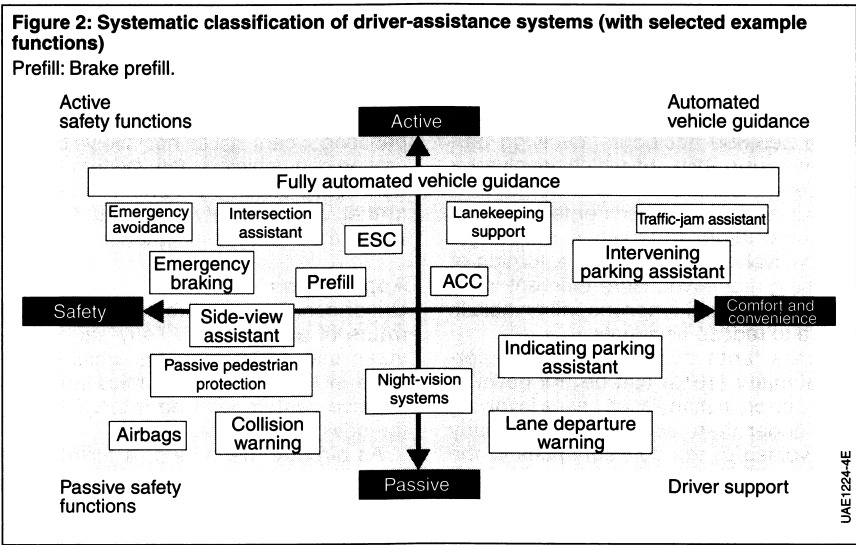
Driver support

Systems for reducing the burden on the driver (driver support) without active vehicle intervention (Figure 2, bottom right quadrant) are the preliminary stage to fully automatic vehicle guidance. These systems give the driver tips on vehicle guidance. The parking assistant with short-range sensors (ultrasound sensors) aids the driver in looking for a

parking space and actually parking, while specific infrared video sensors can be used to good effect to improve driver vision during nighttime driving. In the case of the lane-departure warning system, a video camera uses the road markings to detect the direction of the lane ahead of the vehicle and warns the driver if he/she changes lane without activating a turn signal. The warning can be issued acoustically through the car radio's speakers or mechanically in the form of steering-wheel vibrations.

Automated vehicle guidance

The automated vehicle-guidance systems (Figure 2, top right quadrant) include lane-keeping support, which prevents the vehicle from leaving the lane by means of specific intervention in the lateral guidance. Lane-keeping support is therefore a further development of the lane-departure warning system. Adaptive Cruise Control (ACC) is also one of the automated vehicle-guidance systems. A further development of this system relieves the burden on the driver in slow-moving congested traffic – first by braking the vehicle to a complete stop, and then by moving it forward again at low driving speed (ACC Stop & Go). The



traffic-jam assistant as a further development also permits lateral guidance at low speeds. Significantly higher requirements are imposed on the functions which are intended to facilitate automated longitudinal and lateral guidance on expressways/interstates (expressway/interstate assistant). The next conceivable development step is full longitudinal and lateral guidance in the urban range, i.e. in unstructured environments, at medium speeds (City ACC). Such a system is the last development stage before highly automated vehicle guidance (see Degree of automation).

Active safety functions

The active safety functions (Figure 2, top left quadrant) concern all the active emergency measures for avoiding or mitigating the damage caused by accidents. In the event of a collision danger that can no longer be averted by the driver, these systems in their maximum configuration enables computer-aided maneuvers to be carried out. Collision prevention or mitigation of the consequences is achieved by automated braking (emergency braking, intersection assistant) or steering (emergency avoidance) here. The intermediate steps consist of a brake pre-fill when a danger is detected, short hard braking (kinesthetic warning signal to the driver) or a steering pulse. ESC is an example of an active safety system on the vehicle-stabilization level.

Standard architecture for driver-assistance systems

Driver-assistance systems can be subdivided in accordance with a distributed standard architecture (Figure 3) into the submodules sensor technology, sensor-data fusion (with the aim of creating an environment model), situation analysis (with the aim of understanding a traffic situation and its further development), function (with the aim of action planning), actuator technology, and human-machine interaction.

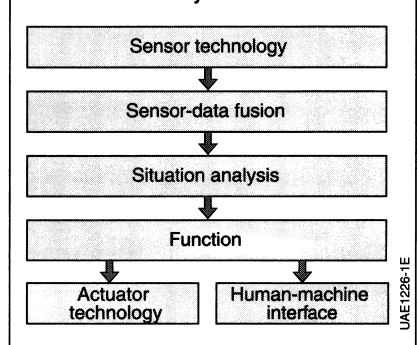
The sensor layer consists of various sensors defined and designed in response to the functional requirements in type and parameterization. In the sensor-data fusion module the environment

is modeled in accordance with the function specification (non-moving environment, function-relevant moving objects) on the basis of the sensor measured values.

In the following situation analysis the criticality with regard to function-relevant scenarios is checked on the basis of environment modeling. Thus, the position of the object and the actual position of the vehicle are predicted into the future by way of example for an emergency-braking function and the risk of collision is evaluated.

The criticality measurements derived in this way serve as the criterion in the following function module for a decision on whether to deploy the function. The function module typically uses a finite state machine which as well as thresholds for the criticality measurements also checks whether the function-specific system limits are adhered to (e.g. in the event of the vehicle being subject to high yaw rates an emergency-braking function would not be triggered for the situation where vehicles are driving in the same direction). In the event of a critical situation the function module runs through a cascade of intervention. This ranges, depending on the situation and function, from early driver notification and warning (visual, acoustic, haptic) to an automated steering or braking intervention to avoid a collision or mitigate the consequences of an accident. The corresponding actuators and the human-machine interface

Figure 3: Standard architecture for driver-assistance systems



are now activated in accordance with the function-specific warning cascade.

Typical approaches for the environment-sensor system, sensor-data fusion and function are described in more detail in the following on the basis of the standard architecture introduced.

Environment-sensor system for electronic all-around visibility

Using “electronic all-around visibility”, numerous driver-assistance systems are achievable – both for passive and for active intervention purposes. Figure 4 shows the detection ranges of the all-around visibility sensors presented below.

Long range

Mainly long-range radar (LRR) sensors are used for long-range applications. Today's sensors have an operating frequency of 76.5 GHz and a range of approximately 250 m. Lidar sensors are also used (e.g. for adaptive cruise control) primarily in Japan. These sensors operating in the close infrared range have ranges of between 150 and 250 m.

Medium range

In the medium range mid-range radar (MRR) sensors with an operating frequency of 24 GHz can meet the exacting demands with regard to range and angle resolution. Since 2005 video sensors have also been used in the medium range. They increasingly play a central role in driver-assistance systems as they enable numerous driver-assistance functions to be implemented due to the large information content of image data (among others thanks to stereo video, optical flow, object classification, see Computer vision) and a very good cost-benefit ratio. For example, infrared cameras in night-vision systems support the driver by detecting situations in the dark.

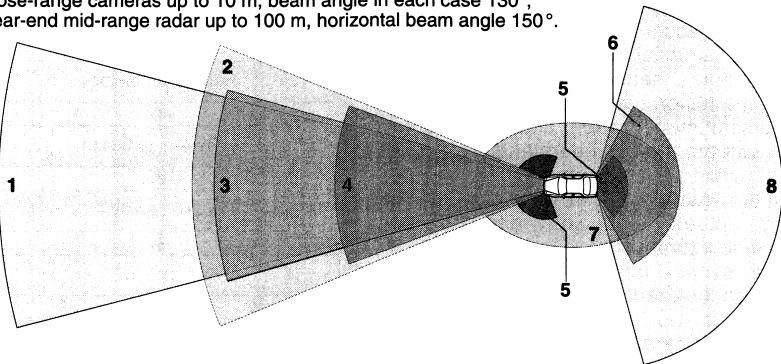
Close range

Ultrasonic sensors with higher scanning ranges than previously can form a “virtual safety shield” around the vehicle within certain limits (range smaller than 20 m). This shield can be used to implement a number of functions. The signals from objects inside this safety shield serves as the database of various safety and

Figure 4: Detection ranges of sensors for vehicle allround visibility

The detection ranges shown as circle segments indicate the beam angle, however the sensor range decreases as the angles get bigger.

- 1 Long-range radar up to 250 m, horizontal beam angle 30°,
- 2 Front-end mid-range radar up to 160 m, horizontal beam angle 45°,
- 3 Night-vision camera up to 150 m, horizontal beam angle 32°,
- 4 Video, stereo video up to 80 m, horizontal beam angle 41°,
- 5 Ultrasonic sensors up to 5 m, horizontal beam angle in each case 120°,
- 6 Reversing camera up to 15 m, horizontal beam angle 130°,
- 7 Close-range cameras up to 10 m, beam angle in each case 130°,
- 8 Rear-end mid-range radar up to 100 m, horizontal beam angle 150°.



comfort/convenience systems. Even the driver's "blind spot" can be monitored by these sensors.

Since 2008 multi-beam lidar sensors have been used to monitor the range up to 8 m ahead of the front of the vehicle for automatic emergency-braking functions and have been rapidly taking hold in the volume segment.

Ultra-close range

The parking assistant monitors the ultra-close range with the aid of ultrasound technology. Today's sensors have a range of up to 5 m. These sensors are therefore suitable for a variety of parking functions. Rear-end video sensors (in their simplest form) can assist the ultrasound-based ParkPilot system during parking maneuvers.

Sensor-data fusion

In the event of long-range functional requirements a number of sensors (based on different sensor principles) can be used with an overlapping field of vision in order among other things to increase the field of vision and improve the accuracy and reliability of object detection. This procedure is known as sensor-data fusion. Thus, the camera mounted at the front end can, depending on its functionality, also be used to extend the measured values of the long-range radar. This enables not only the distance to an object to be measured, but also the object itself to be classified. The object class enables the system to draw conclusions about the position and nature of future object movement and thereby helps to increase the reliability of the function. Connecting the video system to the long-range radar creates synergy effects. This significantly increases the beam angle of the ACC system or lane-keeping support and makes object detection even faster and more reliable.

Future driver-assistance systems will incorporate a large number of environment sensors. Because the sensor data typically arrive at different frequencies and asynchronously and are subject to different time delays, a common time allocation must first be established in the fusion module. This is achieved typically

using ring memory structures and time stamps. The vehicle's surroundings are modeled on the basis of the sensor data. Grid approaches are increasingly being used to model the non-moving (stationary) surroundings [4]. Moving (dynamic) objects are typically modeled as objects with various function-relevant attributes (such as position, expansion, speed) and time-stabilized by means of an algorithm for state estimation (Kalman filter [5]). Hybrid approaches which combine object models and stationary grids are still in the research stage [6].

Operation

Functional processing will be explained in more detail in the following using video sensors by way of example. The video camera is used in the front area for assistance functions, which use for example lanes, road signs or object classes.

The lane-detection system can identify the lane boundaries and the lane direction ahead. If the vehicle is about to move out of its lane unintentionally, the system alerts the driver (see Lane-departure warning system). In a further expansion stage the vehicle – on the basis of lane detection – is moved back to its lane by an active steering intervention (see Lane-keeping support). In combination with ACC a powerful system is created to reduce the burden on the driver in heavy traffic.

Another function that makes use of the information from the video sensor is road-sign recognition. This system is capable of recognizing and interpreting road signs (e.g. speed limit or no-overtaking signs). A video camera takes over 20 images per second and transmits these in the form of a video signal to the image-processing computer. While the vehicle is moving, the system searches for objects which on the basis of their external shape could be road signs (object detection). When such an object is found, it is tracked until it is close enough to be picked up by the video camera as a specific object (object classification). Road-sign recognition presupposes that the designs to be recognized have been taught beforehand into the image-processing computer.

The speed limit recognized and interpreted as such by the image-processing computer (Figure 5) is adopted by the instrument cluster and displayed as a symbol in the graphic display. If the driver fails to observe this speed limit, the system can issue an additional acoustic or haptic warning. Reliable road-sign recognition is now possible at speeds of up to 160 km/h and also in conditions of rain and road spray.

Recognized road signs are increasingly being used in a variety of assistance functions. For example, navigation maps can be updated with recognized road signs and the adaptive cruise control system can in a further expansion stage maintain the vehicle's speed at the identified speed limit.

When a pedestrian is identified as a object class, the function can become active for active pedestrian protection if there is an imminent danger of a collision (see chapter Active pedestrian protection).

A rear-end camera offers greater benefit as against the pure display of the image (rearview camera) if the detected

objects can be interpreted by image-processing software and the driver is alerted in critical situations. This is the case for example if the driver while backing up has failed to see a pedestrian crossing the road.

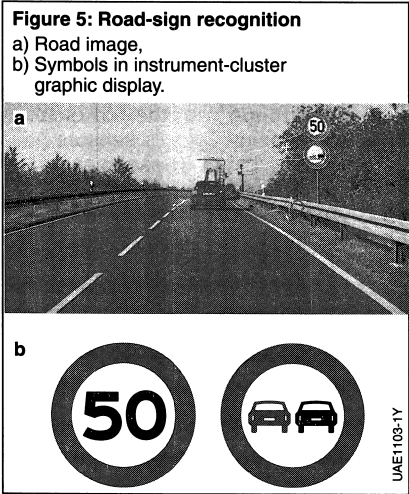


Table 1: Overview of driver-assistance functions

Function name	Warning (W) Longitudinal guidance (Lng) Lateral guidance (Lat)	City (C) Ordinary road (O) Expressway/interstate (E)	Year of market launch	Typical sensor technology
Adaptive cruise control (ACC)	Lng	C, O, E	1998	Radar Lidar (occasionally)
Lane departure warning	W	C, E	2001	Mono video
Lane-keeping system	W, Lat	C, E	2003	Mono video
Roadworks assistant	W, Lng, Lat	E	Open	Mono video Stereo video Radar Ultrasound (side)
Maneuvering assistant	W, Lat	C	Open	Stereo video Mono video (side)
Bottleneck/constriction assistant	W, Lat	C, O	Open	Stereo video
Traffic-jam assistant	W, Lng, Lat	C, E	2013	Stereo video
Intersection assistant	W, Lng	C, O	2013	Radar (side) Mono video
Emergency-braking system (driving in the same direction)	W, Lng	C, O, E	2006	Radar Stereo video
Active pedestrian protection	W, Lng	C, O	2008	Stereo video Mono video Radar

Camera-based sensor technology was initially launched onto the market by way of information-providing driver-assistance systems. Further development of image-processing methods increases the robustness and availability and demonstrates the potential of this sensor technology. Thus, today's video sensors use different approaches to provide three-dimensional measurement of the surroundings, opening up the possibility of new driver-assistance functions.

Table 1 provides an overview of the addressed driver-assistance functions.

Test and hedging

The primary motivation behind active-intervention systems is increasing driving safety, as is the aim for example with an emergency-braking system (AEB) for automatic collision avoidance.

An important aspect of such systems is the risk of incorrect automatic interventions, for example an unauthorized emergency brake deployment. In the worst case this could result in accidents and consequently the increase in system safety would be undermined. It must therefore be possible through suitable measures to rule out such unauthorized interventions with absolute reliability.

In order to determine the achievable benefit and rule out potential risks, comprehensive tests are therefore part and parcel of the development of new driver-assistance systems. How such tests are conducted and the complexity of such tests currently differ depending on whether the purpose is to test the aimed-for effectiveness in critical driving situations or the hedging against unauthorized interventions.

Because critical driving situations, e.g. the rear-end collisions addressed by AEB, fortunately only occur very rarely in ordinary road traffic, the effectiveness is instead analyzed without endangering persons on enclosed test sites and with dummy vehicles.

In contrast to these benefit cases, whose parameters can generally be well described from an accident analysis, the hedging against unauthorized interventions must essentially be conducted for all relevant ambient conditions and driv-

ing situations. For this reason, the vehicle manufacturers and system suppliers conduct very extensive vehicle tests for the purpose of releasing the system [7].

The main reason for the extensive endurance tests lies in the complexity of the environment sensors used, the wide variety of traffic situations, and the high requirements imposed on the safety of autonomous driving-dynamics interventions. This is because, even in a driving situation that is non-critical for the human driver, "phantom" objects may be detected (e.g. a cloud of exhaust gas incorrectly interpreted by a camera as an obstacle). Because unauthorized braking or steering interventions involve a high risk potential, it is essential to ensure that even very rare cases of such incorrect deployments are discovered before the release of the system. This is the reason for the extensive driving tests.

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Computer vision

The computer vision activity field encompasses concepts and methods for extracting information about the surrounding area made up of a static background (e.g. roadway, buildings) and dynamic objects (e.g. pedestrians, vehicles) and scanned by one or more cameras. The three-dimensional environment changing over time is projected into a sequence of two-dimensional image signals through image acquisition, meaning that reconstruction of the environment poses a complex inverse problem [1].

While people appear to be able to handle complex dynamic scenarios without difficulty, machine vision, and consistent interpretation of the image sequence data in particular, also represents a challenging, interdisciplinary activity field after over five decades of intensive research. A large portion of the basic elementary principles behind the image signal processing had already been set in the 1970s and 1980s. This includes operators for filtering image signals, extracting simple geometric structures and matching image signals.

A crucial turning point in the area of environment reconstruction was reached in the 1990s with the development of robust methods for projective reconstruction based on uncalibrated camera systems. The 2000s were characterized by extensive progress in the area of machine learning and the learning-based methods involving detection and classification of objects based on training examples.

Video-based driver-assistance systems such as automatic light control, lane departure warning systems and traffic sign recognition are already available today in a wide variety of vehicles. Future systems will take over complex, safety-related functions and advanced comfort functions and in doing so, will be one step closer to the long-term objective of autonomous driving.

Camera model

Mathematical model

The mathematical model of a distortion-free camera that delivers a perspective map of the 3D environment on a 2D image plane, is described in full using a pinhole camera as shown in Figure 1 [2] with:

$$m = c_x + f s_x \frac{X}{Z} = c_x + \alpha_x x \text{ and}$$

$$n = c_y + f s_y \frac{Y}{Z} = c_y + \alpha_y y$$

From the standpoint of geometrical optics the ray issuing from point in space X passes in a straight line through camera center C and then strikes the image sensor arranged at distance f (focal distance). Through the introduction of the virtual image sensor at the same distance f in front of the camera center all the geometrical proportions (intercept theorem) are clearly retained, but the sign inversion between the camera and the image-sensor coordinates caused by point reflection is avoided. The piercing point of the Z -axis in the plane of the virtual image sensor is called the camera principal point with the coordinates (c_x, c_y) . The scaling factors (s_x, s_y) have the unit [pel/m] and correspond up to the dimensionless pseudo-unit [pel] the reciprocal of the pixel pitch in the x - and y -directions (p_x, p_y) . For an image with $M \times N$ pixels, the whole numbers parts of the image coordinates (m, n) assume values in the range $0 \leq m \leq M-1$ and $0 \leq n \leq N-1$.

The projection center C provides the origin for the camera coordinate system (X, Y, Z) . The Z axis forms the optical axis of the camera that runs through the optical center and is perpendicular to the image plane. (c_x, c_y) defines the main point of the image sensor, i.e. the intersection of the optical axis with the image plane. The (α_x, α_y) parameters of the camera model represent the scaled focal length f (camera constant) in pixel units.

By implementing uniform image coordinates, the camera model can be compactly written as a linear transformation:

$$\begin{pmatrix} m \\ n \\ 1 \end{pmatrix} = KX \equiv \begin{pmatrix} \alpha_x & 0 & c_x \\ 0 & \alpha_y & c_y \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} X \\ Y \\ Z \end{pmatrix}$$

The transformation is conveyed by the calibration matrix K . In this context, the symbol $\equiv$ means equality up to a scalar factor $\lambda \neq 0$.

The inverse transformation K^{-1} yields the standardized camera coordinates:

$$\begin{pmatrix} x \\ y \\ 1 \end{pmatrix} = K^{-1} \begin{pmatrix} m \\ n \\ 1 \end{pmatrix} = \begin{pmatrix} X/Z \\ Y/Z \\ 1 \end{pmatrix} \equiv \begin{pmatrix} X \\ Y \\ Z \end{pmatrix}$$

These result from the scaling with spatial depth Z from the camera coordinates $X = (X, Y, Z)$.

The relationship between the camera coordinate system (X, Y, Z) and the world coordinate system (X', Y', Z') is determined by a Euclidean transformation (R, t) , whereby R represents a (3×3) rotation matrix and t represents a (3×1) translation vector (Figure 2).

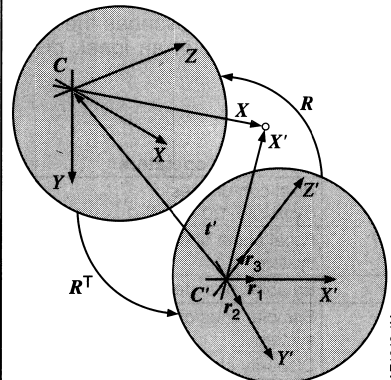
Subsequently, the transformation from world to camera coordinates is then

$$X = R(X' - t') = RX' + t,$$

where t' describes the position vector of the camera center in world coordinates. Accordingly, $t = -Rt'$ represents the origin of the world coordinate system in camera coordinates.

Figure 2: Camera coordinate system (X, Y, Z) and world coordinate system (X', Y', Z') .

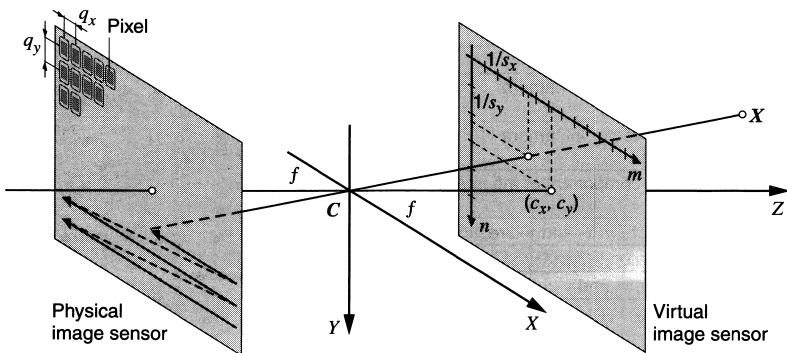
These systems of coordinates are linked via a Euclidean transformation (R, t) , where R denotes a rotation matrix and t the translation vector which points from origin C of the camera coordinate system to origin C' of the world coordinate system.



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Figure 1: Pinhole camera model

Model with physical and virtual image sensor for defining image coordinates (m, n) , camera coordinate system (X, Y, Z) and the parameters for the calibration matrix K . C projection center, f focal length (distance C to the main level of the image sensor), s_x, s_y scaling factors, q_x, q_y pixel pitch, c_x, c_y main point of the image sensor, X pixel.



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These definitions enable the projection of a point in world coordinates to be written to the corresponding image coordinate system as a linear transformation

$$\begin{pmatrix} m \\ n \\ 1 \end{pmatrix} = K(RX' + t) \cong K(R|t) \begin{pmatrix} X' \\ 1 \end{pmatrix}$$

where

$$P = K(R|t)$$

refers to the camera matrix, which has ten degrees of freedom (four intrinsic parameters, three degrees of freedom for rotation, three degrees of freedom for translation) in the case under consideration here and fully describes the transformation geometry of an ideal, distortion-free camera.

Table 1: Symbols and operators.

(m,n)	Pixel coordinates $0 < m < M-1; 0 < n < N-1$
Π, Π'	Focal plane of a stereo camera system
e, e'	Epipoles of a stereo camera system
l, l'	Epipolar lines of a stereo camera system
d	Disparity of corresponding pixels
K	3x3 calibration matrix
R	3x3 rotation matrix
P	3x4 camera matrix
C	Origin of the camera coordinate system
(X,Y,Z)	Camera coordinates
C'	Origin of the world coordinate system
(X',Y',Z')	World coordinates
t	Translation vector in camera coordinates
t'	Translation vector in camera coordinates
I	Luminance component of the image signal
I_x, I_y	Derivation of I in x - and y -directions
∇	Nabla operator
(u,v)	Optical flow, x - and y -components
$\sum_{k=0}^{K-1} x_k$	Sum total $x_0 + x_1 + \dots + x_{K-1}$

Camera calibration

The geometric calibration of a camera includes estimating the intrinsic parameters of the camera, i.e. determining the elements of the calibration matrix K , estimating the parameters of optical distortion and, if necessary, the determining the relative orientation R and translation t between the camera and world coordinate system. In the case of a stereo or multi-camera system, the relative orientation between the two cameras may also need to be determined [2].

For intrinsic calibration, target panels or calibration phantom are used with a number of markers. The detection of the marker in the camera image provides point correspondences in image and world coordinates as input variables for a non-linear optimization problem for estimating optical distortion as well as intrinsic and extrinsic camera parameters.

The target panel depicted in Figure 3 consists of three plates perpendicular to each other with a number of markers and makes it possible to determine distortion parameters as well as the elements of the calibration matrix from a single image. Another option for camera calibration is to use a simple, level calibration phantom recorded under different orientations and positions, so that a large number of point correspondences are available to determine the calibration parameters.

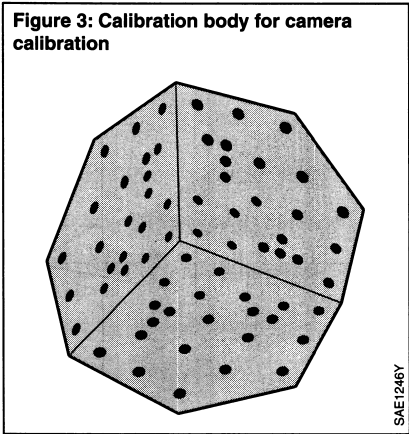


Image processing

Image preprocessing

The photographic sequence provided by the camera generally has to be preprocessed for adaptation to the subsequent image preprocessing steps. This includes aspects such as filter operations for noise reduction or even smoothing and downsampling image data. Methods for the dynamic compression of image data are used to achieve a compact representation for processing and storing the image data, especially for HDR (high dynamic range) image sequences. A representation of the image data on multiple scaling levels in the form of a resolution pyramid is frequently useful to enable a largely scale-invariant postprocessing with limited calculating complexity [3].

Feature extraction

Suitable features are frequently extracted from an image signal for efficient representation and processing of an image sequence. Corners, lines, circles and ellipses provide simple examples that frequently correspond to semantic structures in the environment. This makes it possible, for example, to find lane markings using an edge detector,

which is based on evaluation of the image signal gradient

$$\nabla I = \begin{pmatrix} I_x \\ I_y \end{pmatrix}$$

Here I represents the luminance component of the image signal, while I_x and I_y represent the derivatives of I in the x and y direction of the image plane.

Circles, ellipses and complex geometric structures that possess an sufficiently compact parametric description can also be detected with elementary methods on the basis of image signal gradients. One obvious application is detecting traffic signs, which feature simple geometry and are designed for visual detection in regard to their reflective qualities.

Corner-like structures represent another important class of image features, since (in contrast to line-like structures) they enable point-by-point localization and the formation of correspondences, such as are required for determining the optical flow in an image sequence.

Pattern recognition and object classification

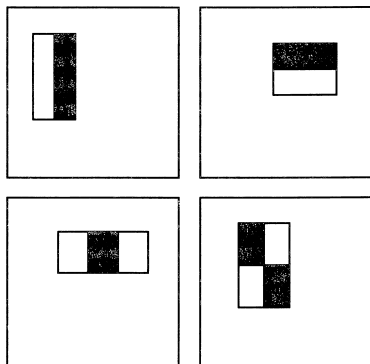
A frequently applied method for pattern or object recognition is based on comparing image regions with predefined texture patterns. If these are limited to the binary texture patterns shown in Figure 4, for example, the integral image

$$S(n, m) = \sum_{n'=0}^n \sum_{m'=0}^m I(n', m')$$

with a luminance value of $I(n', m')$ at position (n', m') results in an efficient implementation with constant computing complexity regardless of the size of the texture pattern. Selecting the difference of the gray values summed by the respective image regions bounded by rectangles as the gap dimension makes it possible to determine the necessary subtotals immediately by referring to the integral image.

Figure 5 demonstrates this principle using the determination of the grayscale value total within the image region with

Figure 4: Elementary image texture pattern for designing efficient object classification methods

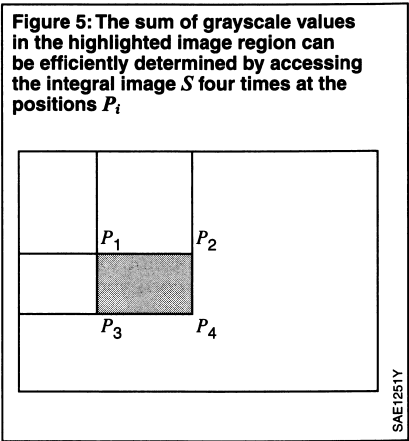


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the corner points P_i as an example. This region is determined by

$$S_R = S(P_1) + S(P_4) - (S(P_2) + S(P_3)).$$

Consequently, the evaluation of the texture patterns as shown in Figure 4 only requires six (two adjoining rectangles), eight (three rectangles) or nine (four rectangles) times accessing the pre-calculated integral image S .



For object classification, classifiers are determined as part of a training process based on example images. The classifiers include increasingly more complex combinations of presented simple texture patterns for object description (Figure 6).

The training process is controlled such that the individual classification levels reach a very high object detection probability, which is associated with a relatively high probability of an erroneous detection by necessity. Very high quality in the overall classifier can be achieved, however, through the cascade structure of the process provided the existence of stochastic independent classification levels.

Although extensive theories on pattern recognition, classification and statistical learning methods already exist, the design engineering of efficient, robust processes for solving object classification problems represents an active research area in real-world applications.

Stereo video

A stereo video camera has two separate optical paths with synchronized image recorders. This enables a spatial 3D reconstruction of the recorded environment based on simple point-by-point triangulation. The measuring principle is depicted in Figure 7 [2].

Figure 6: Object classifier with N stages

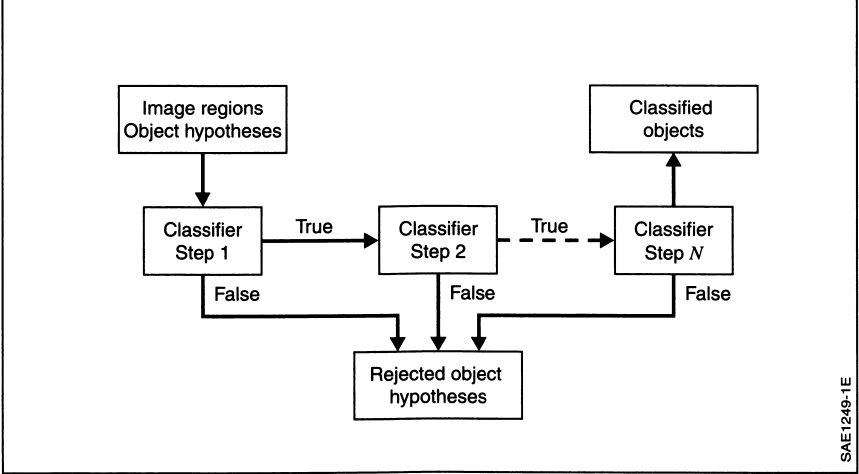
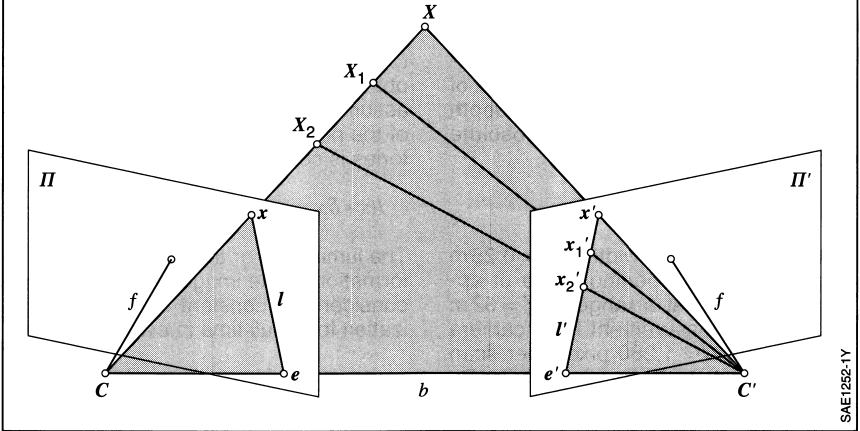


Figure 7: Stereo camera system for explaining the epipolar geometry and one-dimensional point correspondence searching along epipolar lines



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The projection centers (C, C') of the stereo camera system span a stereo base with base width b . The projections of the camera centers on the other respective image plane are referred to as epipoles (e, e'). The camera centers and the reference point X span a epipolar plane where the intersections with the image planes (Π, Π') form the epipolar lines (l, l'). Obviously, pixel x corresponding to pixel x' must lie on epipolar line l' . This means that determining the corresponding pixels of a stereo camera system represents a one-dimensional search problem that can be efficiently implemented accordingly.

A particularly simple geometry results if the optical axes of the stereo camera system are aligned parallel to each other and curve vertically to the spanned base. Here, epipolar lines and image lines overlap, so that correspondences can be sought using the pixels of a single scan line. The difference

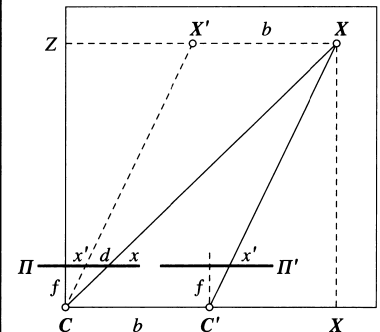
$$d = x - x'$$

means disparity of the corresponding pixels and, in accordance with Figure 8, directly determines the depth

$$Z = \frac{bf}{d}$$

of the reference point X due to the similarity of the triangle $\Delta(C, x, x')$ and $\Delta(C, X, X')$. The 3D coordinates (X, Y, Z) of the observed reference point X are thus completely determined by the disparity d and the coordinates ($x = f X/Z, y = f Y/Z$) of the pixel x .

Figure 8: The geometrical basis for determining the depth Z of the point in space X from the disparity d of the corresponding pixels x and x' creates the similarity of the triangles $\Delta(C, x, x')$ and $\Delta(C, X, X')$.



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The relatively accuracy of the depth estimate is

$$\frac{|\Delta Z|}{Z} = \frac{|\Delta d|}{d},$$

so that a disparity of $\Delta d = 10$ pel is required assuming a disparity estimate of $d = 0.5$ pel to achieve a relative depth estimation error of 5%. The absolute error in the depth estimate is

$$|\Delta Z| = \frac{|\Delta d|}{bf} Z^2$$

and results in a base width of $b = 0.25$ m and a horizontal opening angle of approximately 50° at a range of $Z = 32$ m for a single measurement for a camera system with $M = 1,280$ pixels per scan line, as is in the observed example. By averaging several individual measurements, accuracy and range can be further increased on object planes.

Stereo video systems enable robust implementation of safety-related assistant functions in a vehicle with interaction in the longitudinal and lateral control of the vehicle, such as building and bottleneck assistance and automatic emergency brake systems. This is due to its largely model-free method of operation and direct 3D measurement.

Optical flow

At a given observation time, a velocity vector is assigned to each reference point of the environment via the change in the position vector over time. This motion vector field is thus clearly defined, however, it is not directly observable using the projection of the environment on the image sequence. The vector field from the change over time in the image sequence in relation to a specific vector field is called "optical flow" and does not necessarily have to represent the projection of the motion vector field on the image plane. Deviations are caused by factors such as the reflectance characteristics of the observed objects based on the direction of incident light, changes in lighting over time, moving shadows or superimposed movements in the case of transparent objects. If these phenomena are not dominant, then the optical flow supplies a consistent estimate of the pro-

jected motion vector field, forming an essential component for detecting and interpreting environment scenarios changing over time.

For designing estimation procedures to determine the optical flow from the observed image sequence, it is often assumed that the luminance component of the pixels along the movement trajectories is constant, i.e.:

$$I(x + \delta x, y + \delta y, t + \delta t) = I(x, y, t)$$

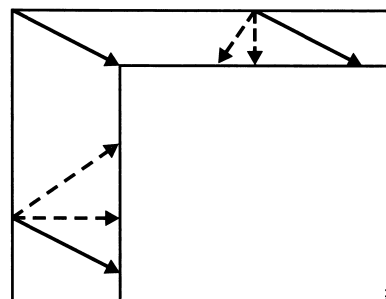
The luminance or the grayscale value information of the image sequence is thus considered a constant that, after linearization for small time intervals where

$$u = dx = \dot{x} dt, v = dy = \dot{y} dt,$$

Figure 9: Aperture problems in estimating the motion vector field (solid lines) from the optical flow

The optical flow is not determined perpendicular to the direction of the grayscale gradient. If only one image section with two vertical or parallel lines is being considered, it is impossible to determine whether the lines are moving vertically with respect to their alignment or at an angle. All plotted vectors satisfy the optical flow equation, so that the motion vector field cannot be completely determined using local methods. Solid lines: Actual direction of motion of the object.

Dashed lines: Possible direction of motion.



yields the optical flow equation

$$I_x u + I_y v + I_t = 0$$

for determining $\mathbf{u} = (u, v)^T$. The spatial and chronological derivations that occur are replaced by corresponding difference quotients during implementation. Using the image signal gradient introduced previously, the condition equation is

$$\nabla I \mathbf{u}^T = -I_t,$$

which means that components of the optical flow can be specified only in the direction of the grayscale gradient. This problem, known as the aperture problem, is provided to illustrate the correlations in Figure 9.

Thus, the estimation problem is under-determined and can only be solved by adding additional ancillary conditions. Assuming that the components of the optical flow in a local neighborhood of each pixel considered are constant, the optical flow equation leads to an over-determined linear equation system, which can be solved with elementary methods, e.g. by minimizing the sum of the quadratic residue.

Modern methods for estimating optical flow avoid the linearization of the optical flow equation and ascribe the estimation problem to the minimization of a suitably selected energy functional.

Efficient numerical methods are available to solve the problem. However, the robust estimation of the motion vector field in the case of difficult ancillary conditions, as they occur in video-based assistant functions in motor vehicles, continue to pose a challenging research and development task.

A significant application of optical flow is estimating movement of the camera itself, which enables 3D reconstruction of the environment. Optical flow, however, can also be used directly for segmenting image content, for example, to detect pedestrians crossing the street or merging vehicles.

3D reconstruction from image sequences

The basic principle of 3D reconstruction of the environment from the chronological image sequence of a camera follows from the camera arrangement shown previously in Figure 7. Now, however, this is not regarded as a chronologically synchronized camera pair in a stereo camera system. Instead, it describes the position and orientation of a moving camera at two points in time. Triangulation, and therefore a 3D measurement of the reference point P , is also possible in this case, provided this is a fixed location during the time interval in question and the camera's own movement. However, only the static environment can be reconstructed now using this method. Since the movement of the camera itself provides the basis required for 3D reconstruction, the method is also designated as "Structure from Motion" (SfM). The related conceptualization "motion stereo" is also frequently used [2].

The core task of the SfM method is to estimate the camera's own movement with sufficient accuracy.

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- [2] R.I. Hartley, A. Zisserman: *Multiple View Geometry in Computer Vision*. 2nd Edition, Cambridge University Press, 2004.
- [3] B. Jähne: *Digitale Bildverarbeitung und Bildgewinnung*. 7th ed., Springer-Verlag, 2012.

Vehicle navigation

Navigation systems

Determination of the position of a vehicle is based primarily on using the GPS satellite positioning system (Global Positioning System). The navigation system compares the determined position with a digital map and uses this map to calculate the route to the specified destination.

Vehicles can be equipped at the factory (original equipment) with permanently installed navigation devices (Figure 1). Portable navigation devices are also in widespread use. Compared with portable devices, permanently installed navigation devices in the vehicle provide better positioning quality and thus better route-guidance quality, since additional sensors for distance and direction signals (wheel-speed and yaw sensors) can be evaluated and the antenna can be mounted in a more favorable place for satellite reception. As original equipment, networking with other components is also common, i.e. integration in the operating concept of the vehicle is possible. Voice outputs can be issued via the audio system and muted for telephone calls. The route-guidance information can be displayed in the instrument cluster or in the head-up display and thus in the driver's primary field of vision.

Functions of navigation

Positioning

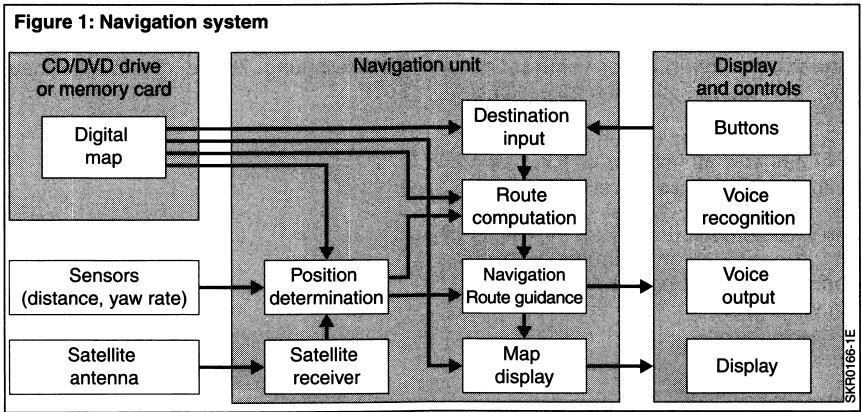
Satellite positioning system GPS

GPS is based on a network of 24 US military satellites which can be used globally for positioning (Figure 2). They circle the Earth in six different orbits at an altitude of approximately 20,000 km in twelve-hourly intervals. They are distributed in such a way that from every point on the Earth always at least four (for the most part up to eight) are visible over the horizon.

The satellites transmit special position, identification and time signals 50 times per second on a carrier frequency of 1.57542 GHz. The satellites each have on board two cesium and two rubidium atomic clocks which vary by less than 20 to 30 ns for the high-precision determination of the transmission time.

Position determination

The signals from the satellites arrive at the vehicle at different times on account of the different propagation times. The position of the receiver is calculated using the trilateration process. When the signals from at least three satellites arrive, the navigation device can calculate its own geographical position in two dimensions (terrestrial longitude and latitude). There is precisely one point which satis-



fies the distance conditions (signal propagation times). When the signals from at least four satellites arrive, this makes possible a three-dimensional position calculation (with altitude). Figure 3 shows this process in simplified form in only two dimensions.

Accuracy

The achievable accuracy is dependent on the position of the satellites that can be received relative to the vehicle. The greater the solid angle of the satellites to the vehicle, the better the possibility of position determination. The achievable accuracy is in the plane approximately 3 to 5 m, and for the determination of height approximately 10 to 20 m.

In deep urban canyons, satellite signals can only be received if the satellites are arranged to a large extent in a line, i.e. in the direction of the street/road. However, the solid angle formed by the satellites is then very small and position determination inaccurate.

Errors in position determination may arise as a result of the reflection of the satellite signals, on metal-coated building fronts, for example.

Travel-direction determination

The direction of travel can be quickly sensed from the differences in the receive frequency of the satellites which are brought about by the Doppler effect. When a car drives towards a satellite, the GPS

receiver of the navigation devices sees a higher frequency than the transmit frequency. It receives a lower frequency from satellites behind. This effect is sufficiently great from a driving speed of approximately 30 km/h to determine the direction.

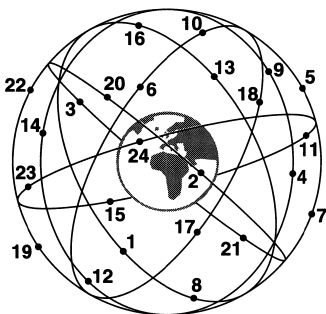
Dead reckoning

Dead reckoning ensures position determination even if no GPS signals can be received, e.g. in tunnels. It adds cyclically recorded distance elements vectorially by magnitude and direction. The speedometer signal transmitted via the CAN bus is used to measure the distance. Changes in direction are recorded by a yaw sensor. In this way, the direction of travel is determined starting out from an absolute determination which was calculated with the GPS signals received last via the Doppler effect.

Map matching

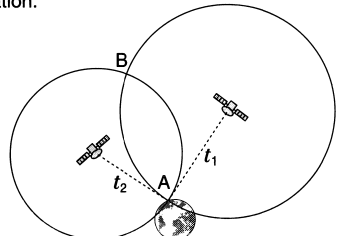
The procedure known as map matching continuously compares the located position with the route on the digital map. In this way, the exact vehicle position can also be shown on the map, even if the located position is inaccurate (caused for example by the lack of a GPS signal and errors in dead reckoning). Route-guidance driving recommendations can thus be output at the best possible location. In addition, sensor errors and cumulative dead-reckoning errors can be compensated.

Figure 2: GPS satellite positioning system
1 to 24 satellites for determining the position of a vehicle.



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Figure 3: Position determination with GPS
(Simplified two-dimensional view). Where the positions of the satellites are known, the possible reception locations for the measured signal propagation times t_1 and t_2 are on two circles around the satellites. The point of intersection A on the Earth is the sought-after location.



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Destination entry

The destination is entered, for example, via the navigation-device panel with buttons, directly via the touchscreen, or by voice input. The user enters all the necessary details from a menu or in response to prompting by acoustically output instructions.

The digital map contains directories so that a destination can be entered as an

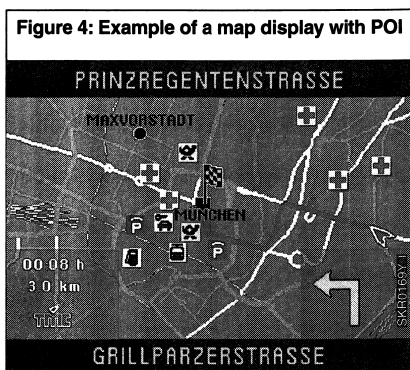
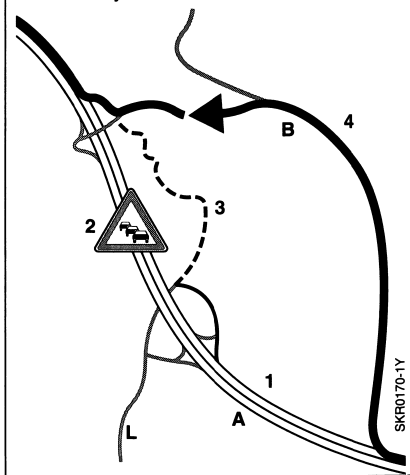


Figure 5: Dynamic route guidance

- 1 Original main route, 2 Congestion,
 - 3 Alternative route estimated by driver,
 - 4 Best alternative route calculated by dynamic route guidance.
- A Interstate/expressway,
B National highway,
L Secondary road.



address. Lists of all known place names are required for this purpose. In turn, all locations are allocated lists containing the names of the stored street names. To pinpoint a destination even further, the user can then also select road/street intersections, or the number of a building.

The destination can be quickly entered via the destination memory, with which already entered destinations can be called up again (e.g. the last destinations used or the destinations saved as favorites).

For airports, train stations, filling stations, multi-storey parking garages, etc. there are thematic directories in which these destinations (POI, Points of Interest) are listed. These directories make it possible, for example, to locate a nearby filling station or multi-storey parking garage (Figure 4).

In many navigation systems, destinations can also be marked in the map display (e.g. via the touchscreen).

Route computation

Standard computation

Starting from the current location, the navigation device calculates a route leading to the entered destination. The way in which the route is calculated can be adapted to suit the driver's preferences. He or she can stipulate different options such as, for example, optimizing the route

- based on driving time,
- based on an economic mean of driving time and driving distance,
- based on an estimated minimum fuel consumption,
- avoiding interstates/expressways, ferry crossings, or toll roads.

Route recommendations are expected within a few seconds of the destination being entered. A more critical scenario is recomputing the route if the driver departs from the recommended route. The new route recommendations must be supplied before the driver reaches the next intersection or junction.

Dynamic routing

Many radio stations transmit traffic messages not only as spoken text, but also in encoded form. The ALERT-C standard for

the Traffic Message Channel (TMC) is provided for this purpose. TMC content is transmitted via the Radio Data System (RDS) of FM radio.

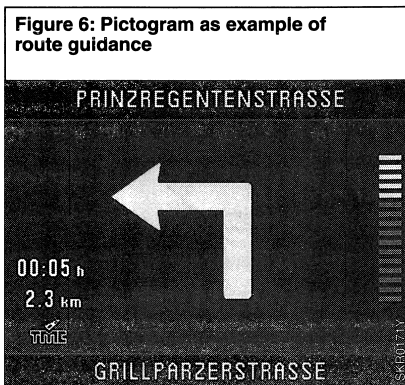
The encoded messages contain, among other things, the location of a holdup, its extent, the actual length, and the reason for it. A navigation system can receive such an encoded message and determine whether a holdup is situated on a planned route. If this is the case, the route is recalculated, where the held-up section is evaluated with a longer driving time. A new route bypassing the holdup may be obtained (Figure 5). Further route recommendations will follow in accordance with the new route.

The TMC codes required for this are limited to interstates/expressways and major highways.

Route guidance

Route recommendations

Route guidance is performed by comparing the present vehicle position with the computed route. Route recommendations are mainly reproduced acoustically (voice output). This allows the driver to follow the directions without being distracted from the task of driving. Graphics, preferably positioned in the primary field of vision (e.g. in the instrument cluster), support the driver in understanding the directions. These graphics range from simple arrow symbols (Figure 6) through to the display of a map excerpt optimally adapted in size (Figure 4).



Digital map

Map display

Depending on the system, the map is represented on color displays using scales as of approx. 1:2,000 in 2D, perspective 2D (pseudo 3D), or real 3D. This is helpful for obtaining a general overview of the route in the immediate locality or over a wider area. Additional information such as, for example, bodies of water, railroads and forests provide added orientation.

Digitization

High-precision official maps and satellite and aerial photographs provide the basis for digitizing the data. If the copies are insufficient or not up to date, on-site measurements/surveys are carried out. Digitization is performed manually from map material or satellite and aerial images. Names and classification of objects (e.g. streets, bodies of water, borders) are then integrated into the database.

Specially equipped vehicles drive along roads to record additional traffic-relevant attributes (e.g. one-way streets, passage restrictions, overpasses and underpasses, no turning off at intersections), after which the initial-digitization data are checked on site. The results from these recording vehicles are incorporated into the database and are used to produce digital maps.

Data memory

Because their storage capacity is at least seven times larger, DVDs have now superseded CDs as the storage medium for digital maps. On the other hand, new systems are mainly being supplied with hard disks or SD cards, where the latter clearly dominate in portable systems. These writable storage media open up the additional possibility of the navigation systems being able to adapt to their users' preferences.

Night-vision systems

Applications

Darkness leads to two significant restrictions to a driver's sense of sight. Firstly, despite modern lighting technologies such as xenon and LED headlamps, only a very limited illuminated field of vision is available. For example, the range of a typical low-beam headlamp is just 50 to 60m. The visibility range can be increased to over 150 m by using high-beam headlamps, this can only rarely be used during night driving, however, due to the tendency to cause glare for oncoming traffic.

Secondly, the capability to recognize objects in the dark by their color and contrast – which differ from those during daylight – is often greatly reduced. Pedestrians wearing dark clothing, for example, are frequently difficult to recognize even when they are within the range of the low beam headlamp. Night-vision systems and cutting-edge headlamp technologies help enormously in this respect to increase road safety.

Camera-based night-vision systems are classified into two different types based on their underlying spectral ranges: far- and near-infrared systems.

Far-infrared systems

Operating principle

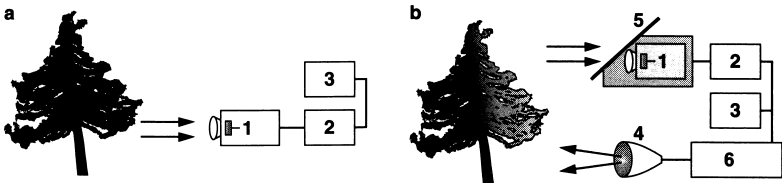
Night-vision systems based on far infrared (FIR) have been used in military applications for years. They use heat radiation in a spectral range between 7 and 12 μm which is relatively far removed from the visible spectral range (hence “far infrared”). They were used for the first time in motor-vehicle applications in 2000 in the USA. They detect with a thermal-imaging camera the heat radiation that is emitted by objects (Figure 1a). These are referred to as “passive” systems since they do not need any additional radiation sources to illuminate objects.

The pyroelectric thermal imaging camera, or microbolometer camera, is only sensitive in the wavelength range of 7–12 μm . Because the glass in the windshield is not transparent for these wavelengths and the camera must be located outside the vehicle.

Thermal imaging cameras use germanium lenses, or tex-glass with high amounts germanium and a corresponding transmission band. Currently available cameras have a resolution up to VGA resolution (video graphics array, 640 $\times$ 480 pixels). The camera signals are processed in an ECU. The generated video signal is output to a display (in the instrument cluster, in the center

Figure 1: Comparison of far-infrared and near-infrared systems

- a) Far-infrared system (7...12 μm),
b) Near-infrared system (780...980 nm).
1 Camera, 2 Electronic control unit (ECU), 3 Display,
4 Infrared headlight, 5 Windshield, 6 Vehicle.



console or in the windshield as a headup display), on which the thermal image can be viewed.

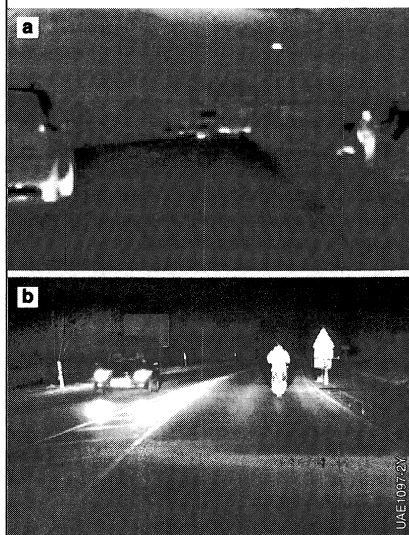
Image display

Hot objects are shown in the image as light contours against dark (cold) surroundings (Figure 2a), where the contrast improves the higher the temperature difference between object and air temperature. However, if a warm object (e.g., a person) is standing in front of a hot tail panel of a tourist bus, he will not be defined by the camera since the sensor is "dazzled".

However, the image display is rather unusual for the viewer since the appearance does not correspond to that of a normal reflected image.

Figure 2: Comparison of the appearance of far-infrared and near-infrared systems

- a) Far-infrared system,
- b) Near-infrared system.



Near-infrared systems

Operating principle

Near-infrared systems (NIR) are based on infrared radiation between 800 and 1000 nm near the visible spectrum (near infrared). Objects do not emit any radiation in this wavelength range. The area ahead of the vehicle must be illuminated with infrared headlamps (Figure 1b). They are referred to as "active" systems for this reason. An infrared-sensitive camera records the scene, i.e., the infrared radiation reflected by the objects. The image signal is transferred to a control unit that in turn forwards the processed image – as in the far-infrared system – to the display. The driver sees – in both systems – a current image of the road situation (Figure 2b) that plays out like a film.

Functioning principle

Near-infrared night-vision systems exploit the different spectral sensitivities of the human eye and electronic silicon-based images. The spectral sensitivity of the human eye is described by the $V(\lambda)$ curve (Figure 3) and comprises the wavelength range from 380 nm (violet) to 780 nm (red). The maximum sensitivity lies in the range of 550 nm (green). Compared to this, the spectral sensitivity of an imager reaches considerably further into the range of high wavelengths, only ending at around 1,100 nm.

Infrared headlamps

Halogen lamps, like those commonly used for automobile headlamps, have a infrared radiation content. This ranges from the limit of the visible spectrum (380–780 nm) up to wavelengths beyond 2,000 nm, with a maximum between 900 nm and 1,000 nm. The upper limit of the useful wavelength when a video camera is used is 1,100 nm, the sensitivity limit of silicon.

Conventional halogen high-beam headlamp models are used as infrared headlamps for this reason. In halogen high-beam headlamp models, visible light is blocked by an additional filter in the light path without significantly reducing the usable infrared part (Figure 3).

The emitted radiation cannot be perceived by the human eye.

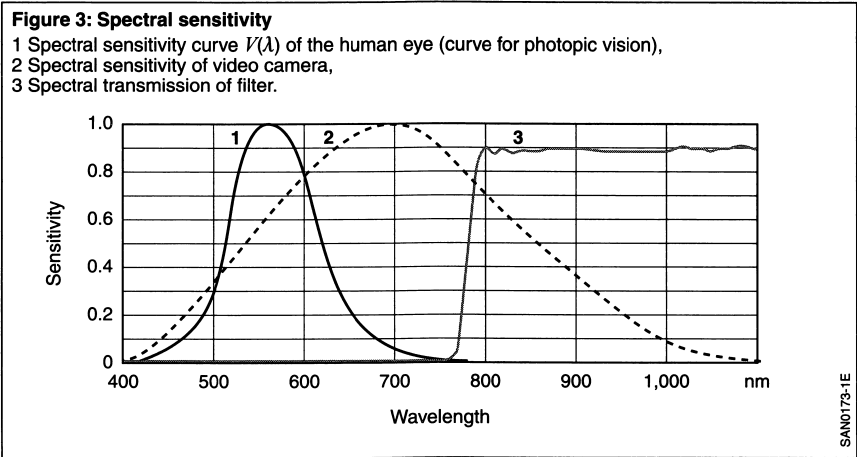
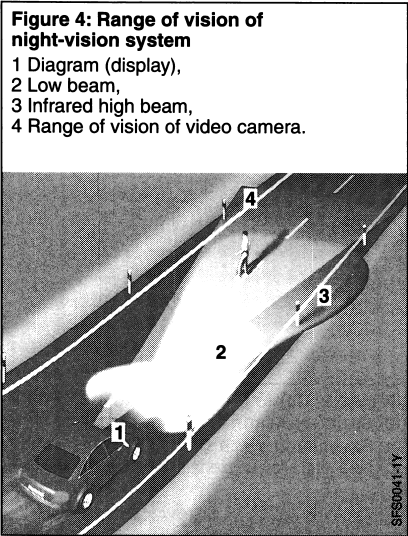
The infrared headlamps that are used have a similar range and spatial characteristics to those of conventional high-beam headlamps, which means that the visual range achieved is comparable but without negatively dazzling other road users (Figure 4).

Suitable selection of the filter characteristic curve takes competing requirements into account. The spectral sensitivity of the imager decreases as the wavelength rises. In order to exploit its sensitive range, the filter edge for low wavelengths should lie near the limit for visible light. On the other hand, in order to prevent non-permitted red impression for front headlamps, the filter edge should be shifted more towards higher wavelengths. Both requirements can be met by carefully selecting the transmission in the visible range, the position of the filter edge, and the edge steepness.

The infrared headlamps are either integrated into the headlamp module or mounted as external modules e.g. in the front apron of the vehicle.

Imagers

The extreme lighting conditions – darkness and very high intensity dynamics, e.g. due to headlamps of oncoming traffic – result in very high requirements for the projection properties of the camera lens, as well as for the imager. The sensitivity to darkness of the imager determines the visual range the system can achieve; the extent of dynamics is deter-



mined to a great extent by the resistance to dazzling.

The CCD chip (Charge Coupled Device) features very high sensitivity to darkness, but as a rule it does not achieve the required intensity dynamics without additional measures. In addition, it tends in the case of large brightness differences in the image to override individual, bright image areas. The CMOS chip (Complementary Metal Oxide Semiconductor) has lower sensitivity to darkness, but does achieve an intensity dynamic of over 100 dB. There needs to be compensation for every pixel of the fixed pattern noise of this technology. Adjustable, nonlinear characteristic curves mean that these imagers can be very easily regulated and adapted to changing lighting conditions.

Lighting up the road scene with radiation in the wavelength range between 700 nm and 1,000 nm (infrared) provides the imager of the camera with a useful signal that depends on the illumination strength and spectral reflective capabilities of the illuminated scene.

Activation strategy

One major aspect of the system is the automatic activation of the infrared headlamps. They emit light of high intensity that the human cannot perceive or can only perceive to a minor degree. To avoid damage to the eyes caused by unperceived exposure at short distances (e.g., mechanics working in the service workshop), the infrared headlamps are only activated automatically when a certain driving speed is reached with the low-beam headlamps switched on. If the speed falls below the threshold, it is automatically deactivated. This excludes occurrence of the critical combinations of long exposure and spatial proximity to the emission source. In addition, the infrared headlamps only light up if the adjacent low beam is also switched on. Through this, the blinking reflex is triggered when the headlamp is looked at, as a result of which the exposure of the eye is greatly reduced.

1st generation night-vision systems

The first system was introduced in 2000 in the American market in Cadillac cars and showed the image of an FIR camera in a head-up display (HUD). This was closely followed by NIR systems in the Japanese market, which also used a head-up display. Due to the high risk of distracting the driver caused by moving images in the primary field of view, these systems were withdrawn from the market after a few years. They could not make the breakthrough in the European market either.

In Japan these first NIR-based systems were initially introduced in 2003 in a simple version in terms of image display and with conventional CCD camera technology. In 2005 an NIR night-vision system with significantly enhanced performance was introduced in the Mercedes S-Class (Night Vision).

In German cars the processed image from the camera (in both far- and near-infrared systems) was displayed in the first systems on a graphics-capable monitor in the instrument cluster (Mercedes) or in the center-console area (BMW). When positioning the monitor in the vehicle, it is important to ensure that the monitor is as close as possible to the windshield and not too far removed from the driver's normal line of sight so that the driver does not have to divert his/her attention from the road and traffic for too long. Ergonomic tests featured the best results in relationship to read-off time and distraction in an arrangement with the monitor in the instrument cluster.

2nd generation night-vision systems

New image-processing procedures enable pedestrians to be reliably classified by reference to their typical outlines (head and shoulder area). This makes it possible not only to warn the driver acoustically but also still to highlight the detected pedestrian on the monitor in order to improve the driver's perception of a dangerous condition. This is particularly important in far-infrared systems, because the image on account of its strange appearance is more difficult to interpret than a near-infrared image.

This feature is important insofar as the majority of fatal accidents involving pedestrians happens at night. In this way, such systems can help to significantly reduce nighttime accidents involving pedestrians. Systems with pedestrian recognition are now fitted as standard in both technologies (near- and far-infrared systems) in German vehicles.

The further development of head-up display technologies offers the additional display of a warning when pedestrians are detected in the primary field of view. Displaying a warning symbol on the windshield represents an effective display format with minimal distractions.

An alternative for simpler systems is a cost-effective optical warning on the base of the windshield that displays the direction of the detected obstacle. These display formats would be a cost-effective alternative for lower classes of vehicles.

3rd generation night-vision systems

New headlamp technologies in the meantime permit the omission of the image display, and as a result the driver is not distracted by looking at the display. A pedestrian detected by the image-processing system can be lit or "flashed" with the aid of a small additional headlamp. This automatically directs the driver's attention towards the pedestrian, who now knows they have been detected.

New pixel-light concepts with numerous high-power LEDs whose light is diffracted by micro-mirrors make it possible to create light cones of almost any shape and facilitate continuous driving on high beam. If a pedestrian or an oncoming vehicle is classified by the imaging system, the light/dark boundary is automatically lowered to such an extent that dazzling no longer occurs.

Parking and maneuvering systems

Application

On virtually all motor vehicles, the bodies have been designed and developed in such a way as to achieve the lowest possible drag-coefficient values in order to reduce fuel consumption. Generally speaking, this trend has resulted in a gentle wedge shape which greatly restricts the driver's rear view when maneuvering. Obstacles are difficult to recognize. This also applies to obstacles beside the vehicle and objects in the driver's blind spot.

Ultrasonic parking aids were initially developed in the past to improve the overview around the vehicle. Thanks to new algorithms and the inclusion of video technology, these systems have undergone further development into maneuvering aids through to (semi)automatic parking systems.

A distinction is made between passive and active systems based on the system configuration. Passive systems warn or inform the driver about hazardous situations, while active systems intervene on a task- and situation-specific basis and steer the vehicle, such as into a parking space.

Ultrasonic parking aid

Parking aids with ultrasonic sensors support parking maneuvers. They monitor an area of approx. 20 cm to 250 cm behind and, if necessary, in front of the vehicle. Obstacles are detected and their distance to the vehicle is indicated by visual or acoustic signals.

Numerous vehicle manufacturers offer parking aids as optional equipment; in many premium vehicles they are now fitted as standard equipment. Systems which can also be adapted to older vehicles are offered for retrofitting.

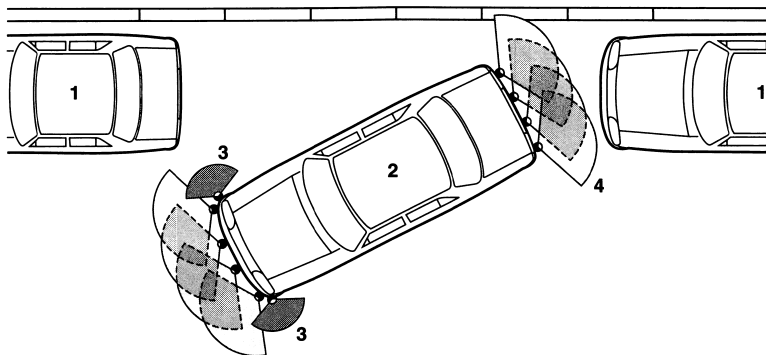
System

The parking aid essentially consists of ultrasonic sensors (see Ultrasonic sensor), the electronic control unit (ECU) and warning elements. The protection area is determined by the range and number of sensors and by their emission characteristic.

As a rule, vehicles with purely rear protection have four ultrasonic sensors in the rear bumper; some large vehicles, e.g. off-road vehicles (SUVs), also use six sensors. Front-end protection is provided by four to six additional ultrasonic sensors in the front bumper (Figure 1).

Figure 1: Scanning range of the parking system with rear- and front-end protection

- 1 Parked vehicle, 2 Parking vehicle, 3 Ultrasonic sensor at the front end,
4 Ultrasonic sensors at the rear end.



For vehicle integration, the installation angle and spacing of the sensors are determined specific to the vehicle. This data is taken into account in the control unit's calculation algorithms. Specifically adapted mounting brackets secure the sensors in their respective positions in the bumper (Figure 2).

The system is activated automatically when reverse gear is engaged. In the case of systems with frontend protection, the system is activated automatically when the vehicle speed drops below a threshold of approximately 15 km/h (manufacturer-specific). During operation, the self-test function ensures continuous monitoring of all system components.

Ranging

The ultrasonic sensors emit ultrasonic pulses and receive the sound reflected by an obstacle (Figure 3). The piezoceramic element generates an analog electrical signal, which is evaluated in the sensor (see Ultrasonic sensor).

Echo-sounding method

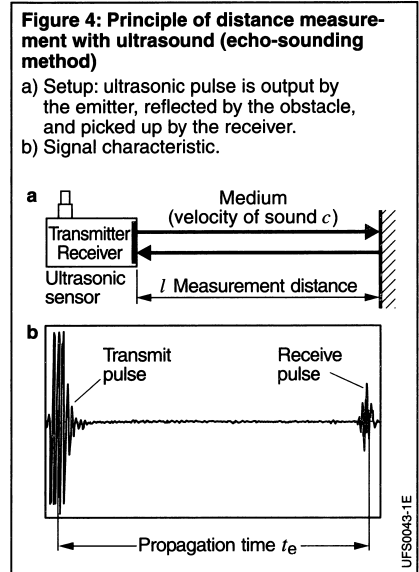
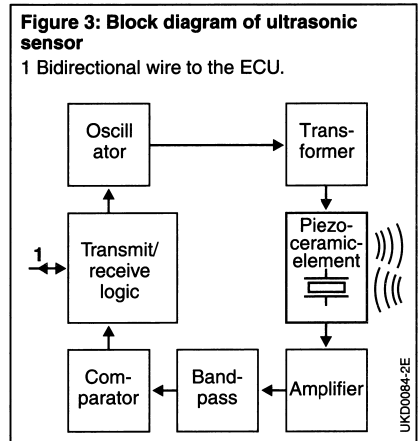
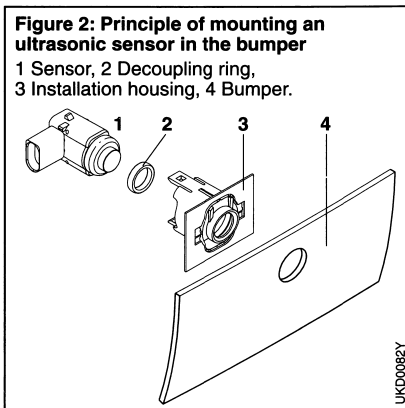
Following the echo-sounding method (Figure 4), the ultrasonic sensors detect the time taken between the ultrasonic pulses being emitted and the echo pulses being reflected back from obstacles. The distance l between the transceiver probe and the nearest obstacle is derived from the propagation time t_e of the first echo

pulses and the velocity of sound c according to the following equation:

$$l = 0.5 t_e c$$

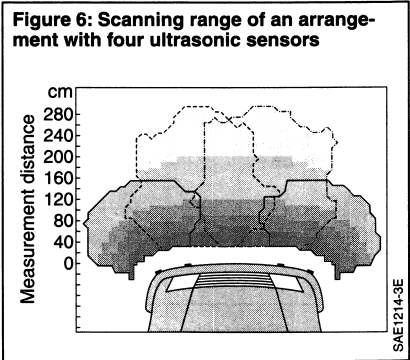
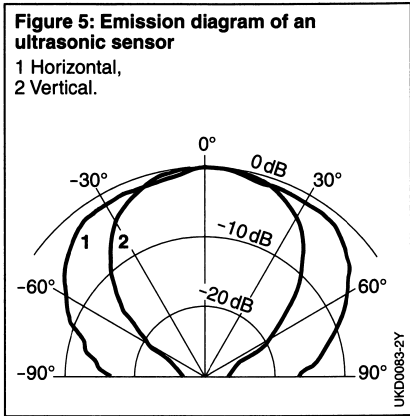
with

t_e propagation time of ultrasonic signal,
 c velocity of sound in air ($c \approx 340$ m/s).



Detection characteristics

To enable the system to cover as large a spatial area as possible, the detection characteristics must meet special requirements. In the horizontal direction, a wide detection angle is desirable; in the vertical direction, on the other hand, a compromise is required. In order to avoid interference from ground reflections, the detection angle must not be too wide. However, existing obstacles must be reliably detected. Figure 5 shows the emission characteristic in the horizontal and vertical planes. A nearly seamless scanning range is produced by the overlapping scanning ranges of multiple sensors. Figure 6 shows an example of the scanning range of a 4-channel system.

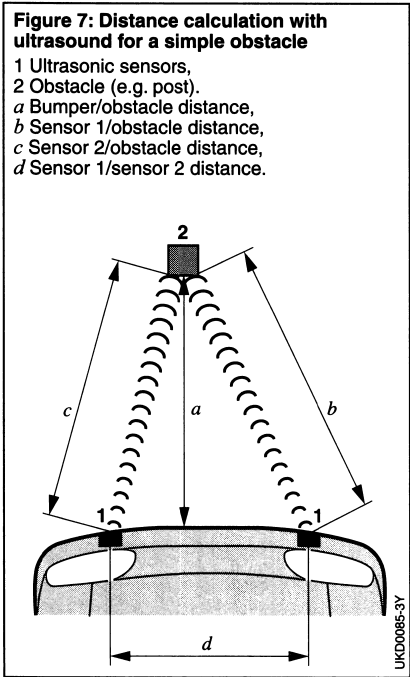


Newer-generation sensors also allow for a variation of the vertical detection angle within certain limits, thus permitting optimized adaptation to the geometry of the bumper and vehicle without resulting false warnings in the event of bumps.

Distance calculation

The geometrical distance a between an obstacle and the front of the vehicle is determined using the triangulation method from the results measured (distances b and c) from two ultrasonic sensors, mounted at a distance d from one another (Figure 7). The distance a is calculated from the following equation:

$$a = \sqrt{c^2 - \frac{(d^2 + c^2 - b^2)^2}{4d^2}}$$



Electronic control unit (ECU)

The ECU contains a voltage stabilizer for the sensors, a microcontroller, and all the interface circuits needed to adapt the different input and output signals. The software assumes the following functions:

- Activating the sensors and receiving the echo
- Evaluating the propagation time and calculating the distance to the obstacle
- Activating the warning elements
- Evaluating the input signals from the vehicle (e.g. signal for engaged reverse gear)
- Monitoring the system components including fault storage
- Providing the diagnosis function

Warning elements

The warning elements display the distance from an obstacle. Their design is specific to the vehicle, and they usually provide for a combination of acoustic signal and optical display. Primarily LEDs, but also LCDs are currently used for optical displays.

In the case of vehicles with a display monitor in the center-console area or in the instrument cluster, the vehicle can be shown together with the obstacles detected by the system, e.g. from a bird's eye view. This generally improves the driver's view of the situation.

Ultrasonic parking assistant

The parking assistant is based on the ultrasonic parking aid and is designed along evolutionary lines in stages. Each stage is a self-contained function.

All the ultrasonic systems shown in the following are already in series production.

Parallel parking

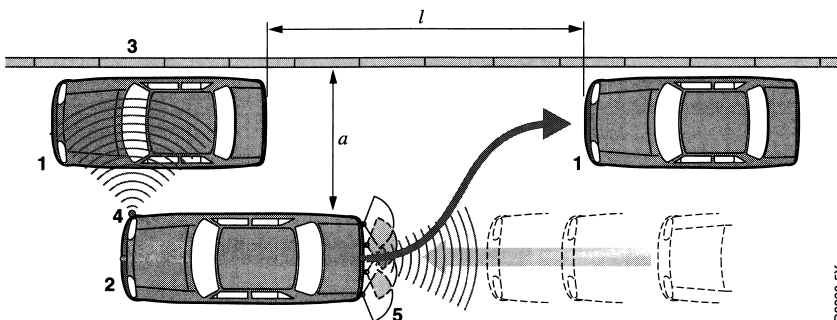
Information-providing parking assistant

After the system is activated by the driver, an ultrasonic sensor mounted on each side of the vehicle measures the length and depth of the parking gap as the vehicle drives past the gap (Figure 8). The length is obtained by evaluating the ESC speed signal (ESC, Electronic Stability Control, driving-dynamics control). The parking assistant then issues the driver with a signal as to whether the parking gap is long enough, tight or too short. If there is an obstacle in the parking space, this is rejected. This requires the above-mentioned sensors with a range of up to approximately 4.5 to 5.5 m.

Once the parking space has been measured, the determined geometry of the environment can be used to ascertain the optimal trajectory for the parking process. The parking assistant requires the signals from the steering-angle sen-

Figure 8: Parking assistant

- 1 Parked vehicle, 2 Parking vehicle, 3 Parking space boundary (e.g. curb),
4 Side-detecting ultrasonic sensor, 5 Ultrasonic sensor in the rear area.
 a Measured depth of the parking space, l Length of the parking space.



sor (from the driving-dynamics control, ESC) for this purpose. During the parking process, the system can now give the driver a recommendation regarding how he or she should optimally turn the steering wheel in order to park in the space as smoothly as possible. During the parking

operation, the trajectory is continuously recalculated and shown in a display. Figure 9a shows an example of a driving recommendation from the system.

Steering parking assistant

The next evolutionary stage is a system with automatic steering activation. A prerequisite is that the vehicle must have electrically activated power steering.

As before, the driver has to inform the system of his or her desire to park by pressing a button. After the system measures the parking space, the driver is notified whether the length of the parking space is sufficient. This can be accomplished for example by a corresponding graphics display in the instrument cluster (Figure 9b). Now the driver simply needs to put the vehicle in reverse and control the vehicle's linear motion (by braking and accelerating) – the parking assistant takes over the steering. When the parking process is done, the driver is notified accordingly.

One-step and multi-step parking

In the case of both the information-providing and the steering parking assistant, the system decides whether to park in one step or multiple steps, based on the length of the parking space. One-step parking is always selected if the parking space is long enough. If the parking space is short, the parking assistant decides on multi-step parking, based on the length of the space and the vehicle's

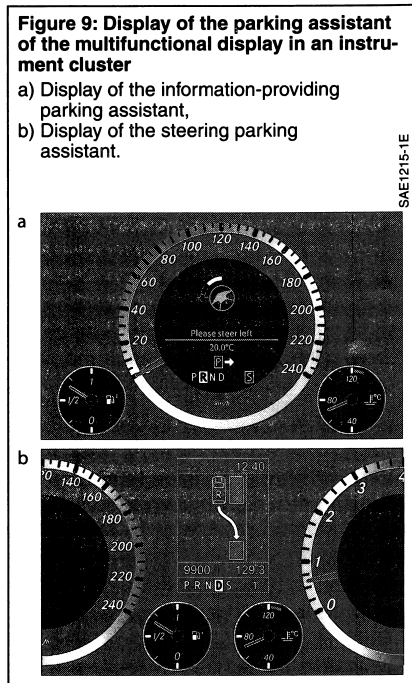
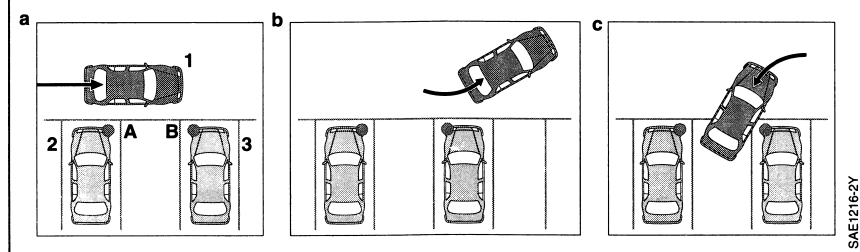


Figure 10: Perpendicular parking
a) Detection corner point A, b) Preparation for parking, c) Parking in the parking space.
1 Parking vehicle, 2 Left parked vehicle, 3 Right parked vehicle.
A Right corner point of the left parked car,
B Left corner point of the right parked car.



possible steering radius. Then the system prompts the driver to shift gears accordingly.

Perpendicular parking

Semi-automated parking is not limited to the parallel parking functions described, but also permits parking in spaces perpendicular to the direction of travel (Cross-Parking Assist, Figure 10).

As with parallel parking, the length of the parking space is measured as you drive by it. To do this, the corner of the vehicle on the left (marked as corner point A in Figure 10) is taken as the initial reference point for the parking maneuver. If there is also a vehicle to the right of the parking space, its corner (corner point B) is also taken into account.

Before beginning the parking process, the vehicle moves forward until it can calculate a parking trajectory. Then, after reverse gear is engaged, the vehicle parks along the trajectory, which is continuously recalculated and corrected if necessary. The signals from the rear ultrasonic sensors are continuously factored into the parking maneuver. Due to the limited detection range of the ultrasonic sensors, the driver is responsible for making sure the entire length of the parking space is free of obstacles.

As with the previously described parking assistants for parallel parking, for this function there are also information-providing and – if the vehicle is equipped with electric power steering – steering system versions.

Assistant for leaving a parking space

In principle, the parking aid can also be used for leaving parallel parking spaces. To do so, the system first moves the vehicle into an appropriate starting position, so that the maneuver can be done in one step. The driver is responsible for paying attention to the traffic and accelerating or braking at the right moment. Simply touching the steering wheel turns off the function.

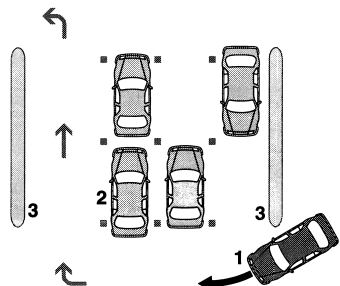
Maneuvering assistant

Traces of paint on parking-garage pillars and walls testify to frequent, sometimes costly collisions with vehicles. The system for warning about objects next to the vehicle helps prevent that.

Ultrasonic sensors mounted on the front of the vehicle at the sides detect permanent obstacles in the vehicle surroundings at a slow driving speed (up to 30 km/h) (Figure 11). The maneuvering assistant saves their positions, so that these are known even after the obstacles are no longer in the scanning range of the sensors. The side distance to the saved obstacles is continuously calculated using the steering angle sensor signal. If a risk of collision is detected, the driver receives an audible warning (side distance warning). A bird's-eye view of the situation can also be shown on the central display. This system was introduced to serial production in 2013.

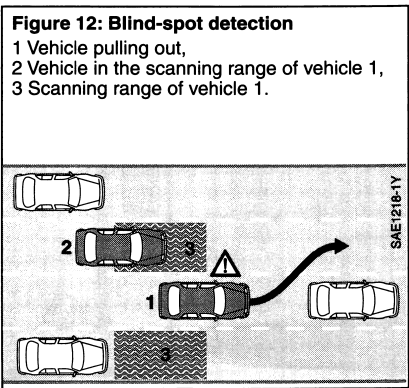
Figure 11: Maneuvering assistant

1 Vehicle driving into a parking garage,
2 Parked vehicles, 3 Obstruction.



Blind-spot detection

Blind-spot detection (side-view assist) makes use of two more ultrasonic sensors installed in the rear end at a horizontal angle of about 45° to the direction of travel, in addition to the two ultrasonic sensors already installed in the front end at a 90° angle to the direction of travel. All four sensors have an increased range of up to 5.5 m. The front sensors are used to suppress warnings of oncoming vehicles and stationary objects. On roads with only two lanes, therefore, the system does not issue a warning about oncoming traffic or vehicles parked on the side of the road. The rear sensors detect objects in the vehicle's blind spot (Figure 12). Dangerous situations are identified from the position of detected vehicles and their movement relative to the driver's vehicle, and the driver is alerted. This system was introduced to serial production in 2010.



Video systems

Rearview camera

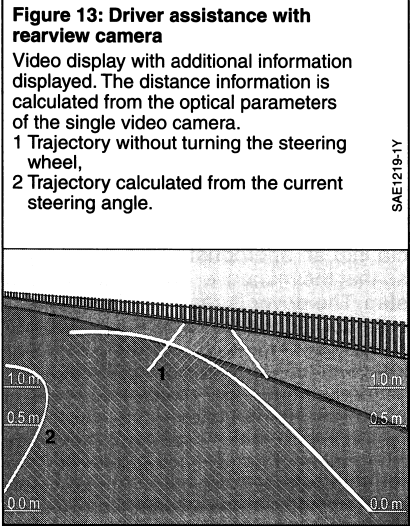
Rearview cameras were already first introduced some time ago in Japan, but did not become prevalent in Europe due to the heavily distorted picture of the super-wide-angle lens. The breakthrough in Europe didn't come until there were systems to correct the image distortion.

Today's systems have a wide-angle camera installed in the rear end of the vehicle, usually in the recess of the handle to the trunk. The camera image appears in the center console display when driving in reverse. Newer systems with additional lines to help estimate the distance and display the predicted lane make it easier for the driver to maneuver (Figure 13).

The camera is intended only to provide information and does not provide the driver with any warnings.

Front-end camera

Visibility all around the front of the vehicle can also be provided by a video camera with a 180° wide-angle lens. It also provides a view of traffic from the sides, for example, when pulling out of a driveway (Figure 14). Since the driver is seated



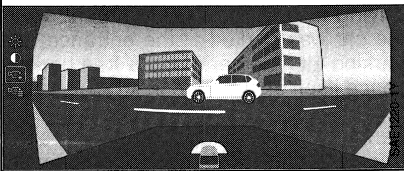
farther back in the vehicle, the view from there is not as good as from the camera installed in the front of the vehicle.

360° all-around visibility

The whole area around the vehicle can be detected using four super-wide-angle cameras installed around the vehicle (top-view system, Figure 15). The fields of view of the individual cameras overlap in the shaded areas. The four individual images are converted into one overall image using the stitching method. Projecting the four images into an imaginary bowl structure makes it possible to provide the driver with a bird's-eye view and a view from different directions of his or her own vehicle in the display.

Figure 14: Driver assistance with front camera

View of the main road when driving out of a private driveway.



Fusion of video and ultrasound technology

Further improvements can be achieved through data fusion of the ultrasound system's signals with the video camera's signals. For example, in addition to the lane information, distance information from the ultrasound system can be displayed in the image from the mono rear-view camera as well, which cannot be used for measuring distance (Figure 16). By doing so, the driver receives even more meaningful information about the area by the rear of the vehicle.

Figure 16: Video image with distance information of the ultrasonic sensor

- 1 Obstacle (e.g. wall),
- 2 Distance assistance lines on the 50 cm grid, calculated from measured values of the ultrasonic sensors,
- 3 Trajectory at maximum steering angle.

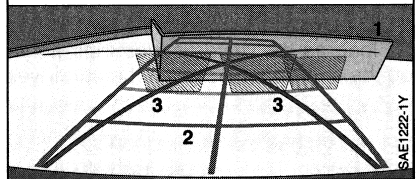
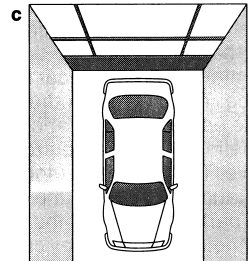
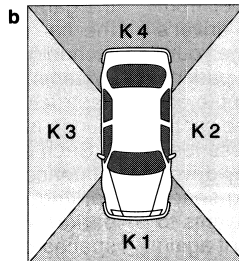
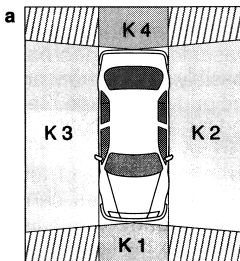


Figure 15: 360° all-around visibility with four cameras

- a) Detection range of the cameras (shaded areas indicate where they overlap),
 - b) Strictly defined image borders for the top view image,
 - c) 360° all-around visibility from a bird's-eye view (parking garage example).
- K1 to K4 Cameras on the front, rear and sides of the vehicle.



More recent development steps

Further functions and options have been created through the further development of semi-automatic parking by using intelligent image-processing algorithms (see Computer vision). The combination of intelligent camera systems with ultrasonic sensors form the basis for the automated parking and maneuvering assistance systems outlined in the following.

*Parking maneuver assistant
(park maneuver control)*

Further development of the steering parking assistant has the vehicle now controlling linear motion as well. To initiate the parking maneuver, the driver needs only to put the gear in reverse; the system handles the rest. This system was launched into series production in 2014.

*Remote-controlled parking assistant
(remote park assist)*

The driver drives past a parking space and receives a signal from the parking assistant if the space is sufficiently long. The driver gets out of the car and taps the "Parking" function on their smartphone. As long as the driver leaves their finger on the smartphone screen the car drives along the previously calculated trajectory into the parking space. If during the parking maneuver a critical situation arises (e.g. pedestrian crosses the trajectory), the driver simply has to take their finger off the screen and the car will stop immediately.

Home-zone park assist

In parking garages or parking lots with reserved parking spaces in the home environment it will in future be possible to teach the car a parking maneuver from a defined parked position to the driver's own parking space by driving the route and maneuvering the car into the parking space. The driver can then leave the car in the parked position and start the car by actuating a remote control as described above. The car then automatically drives the taught course to the parking space and parks up there. If the driver wants to use their car again, they can fetch it again from the garage with the same remote

control. The car will then stop in the original parked position.

Highly automated, remote-controlled parking (remote park pilot)

This function is used above all for maneuvering into and out of tight garages or parking spaces. Because it is in principle possible to park a car without the need for a driver, the user can start the parking operation in front of the garage with a remote control, an intelligent remote key, or their smartphone by touching an operating element. The car then drives automatically into the garage. The driver does not need to be present for this. This function calls for very robust environment recognition and high safety requirements.

This system was launched into series production in 2016.

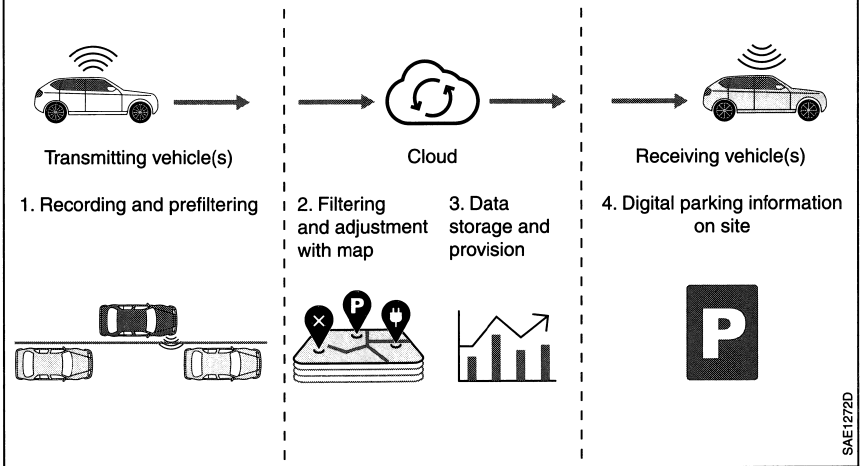
Autonomous parking (automated valet parking)

A car that parks autonomously was presented to the public for the first time in 2007 as part of the American "Urban Challenge", a competition for automatic driving in an urban environment. Here the car was parked at the entrance to a parking lot. The car found a free parking space itself and parked in it [1].

With this new function too the car is parked in a predefined drop-off area in front of a parking garage or a basement garage. For the subsequent parking maneuver the driver gets out of the car and selects the "Find parking space" function on their smartphone. The car drives fully automatically into the parking garage, finds a parking space itself, and parks in it. The same operating procedure can be used to fetch the car from the garage. For driving and maneuvering the car uses its own on-board sensor technology (ultrasonic and video-based systems) and possibly signals from an infrastructure of the parking garage. Series launch is planned for around 2020.

Such systems can have a significant influence on the infrastructure of future parking garages: The vehicles can be parked much more tightly since large spaces do not have to be kept for getting in and out. The storey height can be

Figure 17: Autonomous parking with Vehicle to Infrastructure Communication



reduced. Long-stay parked vehicles can be “blocked in”.

Networking with the “Cloud”, Connected Parking

Looking for a parking space involves driving unnecessarily long distances. The resulting fuel consumption and exhaust emissions add up to a huge environmental impact.

Remedial action can in future be taken by a system which actively supports the driver in looking for a parking space. This system is based on the interaction between vehicles and infrastructure (V2I, Vehicle to Infrastructure Communication, Figure 17). Vehicles which are situated in an area with parking spaces (e.g. in an urban area) detect the geographical location of available parking spaces and their length with their on-board sensor

technology and transmit this information to a “Cloud”. In the Cloud the data are filtered and the parking position is inserted into a map. All the relevant information is stored and made available to possible users. As shown in Figure 17 by way of example, the driver receives information on occupied and vacant parking spaces and parking spaces with a charging station. Vehicles looking for a parking space can download the information from their surroundings from the Cloud and receive route-direction information to a neighboring vacant parking space or to a parking space as close as possible to the input destination in the navigation system.

References

- [1] <http://www.urbanchallenge.com/>

Adaptive Cruise Control

Function

Like the basic cruise-control system that has been available as a standard feature for quite some time, Adaptive Cruise Control (ACC, also known as Tempomat) can be categorized as a driver-assistance system. The vehicle-speed controller regulates the driving speed to the desired speed set by the driver using the operating unit of the cruise control. In addition to this function, adaptive cruise control senses the distance and the relative speed for the vehicle in front and uses this information with additional data from the driver's own vehicle (e.g. steering angle, yaw rate) to regulate the time gap between the vehicles. It thus adapts the speed to the vehicle ahead and maintains a safe distance. The adaptive cruise control is equipped with a long-range radar to detect vehicles that are traveling in front in the same lane or also obstacles that are moving in the sensor's sensing range, and necessitate that the vehicle be braked (Figure 1).

Design and function

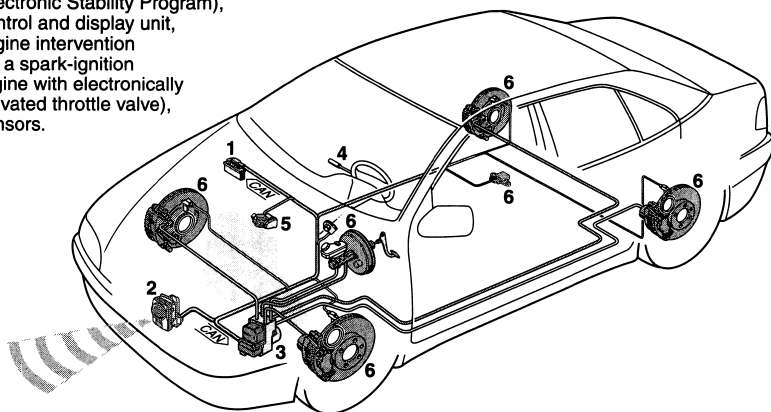
Adaptive cruise control is a convenience system that relieves the driver of routine tasks, but not of his/her responsibility to maintain control of the vehicle. This is why the driver can override this function at any time through intervention or deactivation (e.g. by operating the accelerator or brake pedal).

Ranging sensor

Current ACC systems for the most part have a radar sensor which operates in a frequency range of 76 to 77 GHz (see Radar sensors). The radar beams emitted by the radar sensor are reflected by vehicles ahead and analyzed with regard to propagation time, Doppler shift, and amplitude ratio. These values are used to calculate the distance, speed, and angle position relative to the vehicles ahead. The evaluation and control electronics (radar-sensor check unit) are integrated in the sensor housing. They receive and transmit data via a CAN data bus from

Figure 1: Adaptive cruise control for a passenger car

- 1 Engine control unit,
- 2 Radar-sensor control unit,
- 3 Active brake intervention via driving-dynamics control (Electronic Stability Program),
- 4 Control and display unit,
- 5 Engine intervention (on a spark-ignition engine with electronically activated throttle valve),
- 6 Sensors.



or to other electronic control units that influence the engine torque and brakes (Figure 2).

There are also ACC systems that work with laser beams in the infrared range (see Lidar, Light Detection and Ranging). The functioning principle is similar, whereby the use of an optical beam means that restrictions compared to the radar systems must be accepted in poor weather conditions (fog, rain, snow) (see e.g. [5]).

Course setting

To ensure reliable ACC operation no matter what the situation – e.g. also on curves/bends – it is essential that the vehicles traveling ahead can be allocated to the correct lane(s). For this purpose, the information from the driving-dynamics control (Electronic Stability Program) sensor system is evaluated with regard to the ACC-equipped vehicle's own cornering status (yaw rate, steering angle, wheel speeds, and lateral acceleration).

Setting options

The driver inputs the required speed and the required time gap; the time gap available to the driver ranges from 1 to 2 s. The time gap to the vehicle in front is calculated from the radar signals and compared with the required time gap

specified by the driver. If the time gap is shorter than the required gap, the ACC system responds in a manner appropriate to the traffic situation by initially reducing engine torque, and only if necessary by automatically braking the vehicle. If the required time gap is exceeded, the vehicle accelerates until either the speed of the vehicle ahead or the desired speed set by the driver is reached.

Engine intervention

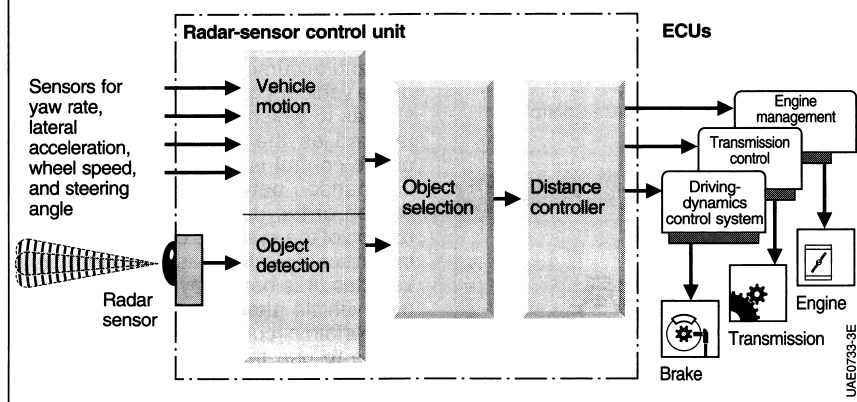
Cruise control is run via the electronic engine-performance control system (e.g. Motronic, electronic diesel engine control). This system allows the vehicle to be accelerated to the required speed or, if an obstacle appears, to be decelerated by reducing the drive torque.

Brake intervention

If the deceleration caused by engine control intervention is insufficient, the vehicle must be braked. For passenger cars the driving-dynamics control (Electronic Stability Program) is required for this purpose; this can perform a brake intervention. For commercial vehicles, an electronic braking system (EBS) is sufficient. Usually, this also involves the available retarder or engine brake for wear-free deceleration.

Due to the configuration of ACC as a comfort system, the deceleration calcu-

Figure 2: Basic structure of ACC system



lated by the controller is limited nowadays to approx. 2 to 3 m/s². Should this be insufficient due to the current traffic situation (e.g. vehicles in front braking sharply), a visual and audible signal is issued to the driver indicating that he or she must assume control. The driver must then initiate the corresponding braking deceleration via the standard brake. The ACC does not include safety functions such as emergency braking.

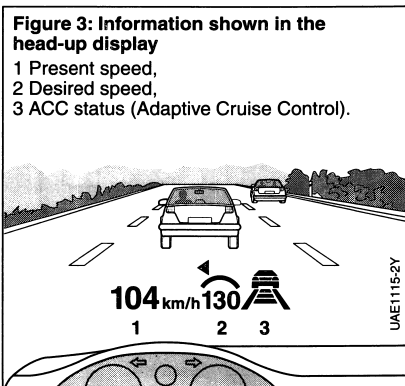
If necessary, with ACC activated, the stabilizing systems Antilock Brake System or driving-dynamics control are activated in the usual manner. Depending on the parameterization of ACC, stabilizing interventions from the Antilock Brake System or driving-dynamics control cause ACC to shut off.

Display

The driver must be provided with at least the following information:

- Display of the desired speed
- Indication of the switch-on status
- Indication of the required time gap selected by the driver
- Indication of the follow-up mode, which informs the driver as to whether the system is controlling the distance to a detected target object or not.

The information can be displayed, for example, in the instrument cluster or in a head-up display (Figure 3).



Control algorithms

Control modules

As a general principle, the control system for cars as well as for trucks consists of three control modules.

Cruise control

If the radar sensor has not detected any vehicles in front, the system maintains the vehicle's speed at the cruising speed set by the driver.

Tracking control

The radar sensor has detected vehicles in front. Control essentially maintains the time gap to the nearest vehicle at a constant setting.

Cornering control

When negotiating tight bends, the radar sensor can "lose sight" of the vehicle in front because of the limited width of its field of vision. Until the vehicle comes in sight of the radar again, or until the system is switched to normal cruise control, special measures come into effect. Depending on the vehicle manufacturer, the speed, for example, is kept constant, current lateral acceleration is adapted or ACC is switched off.

Object detection and lane allocation

The central task of the radar sensor and its integrated electronics is to detect objects and allocate them either to the same lane as the one on which the truck is traveling, or to a different lane. This lane allocation requires both exact detection of vehicles ahead (high angle resolution and accuracy) and exact knowledge of the vehicle's own movement. The decision as to which of the detected objects is used as the reference for adaptive cruise control is essentially based on a comparison between the positions and motion of the detected objects and the motion of the system's own vehicle. Here, in particular in the case of commercial vehicles, it is not always necessarily the next vehicle ahead that is selected. Under certain circumstances, it makes better sense to use the next vehicle but one, e.g. when a passenger car filters in from

the slip lane and continues rapid acceleration to change quickly to the fast lane.

Electronic structure

Apart from the data transmitted by sensors (Figure 2), ACC requires additional data from the engine, retarder (for commercial vehicles), transmission and driving-dynamics control units, and which are transmitted via the CAN data bus. Conversely, these control units convert the accelerations requested by ACC into drive and braking torques. The coordination of the actuators (e.g., distribution of the required braking torque to the available brakes) can take place both in the driving-dynamics control unit and in a guidance computer or in the ACC control unit itself.

Adjustment

The radar sensor is fitted in the frontal area of the vehicle. Its radar lobe scans are aligned relative to the vehicle longitudinal axis. This is done by means of the adjustment screws in the mounting area of the sensor. If it is moved out of alignment by physical force, e.g. deformation of the mounting due to accident damage or any other effect, realignment must be carried out. Small degrees of misalignment are automatically corrected by the permanently active alignment routines implemented in the software. If manual realignment is required, this is indicated to the driver.

Area of application and functional expansions

Use in passenger cars

The use of Adaptive Cruise Control is bound to the availability of driving-dynamics control. This is a requirement for active brake intervention without action on the part of the driver.

Use in commercial vehicles

Requirements

Some of the general conditions for a commercial vehicle ACC differ significantly to those for a passenger car ACC:

- Regulation of braking and acceleration must take account of the widely variable parameters of payload and engine size.
- Overtaking and merging maneuvers follow a dynamic pattern that is slower on trucks than on cars, and therefore result in different control requirements and settings.
- The control dynamics must be capable of handling a situation where several vehicles equipped with ACC are driving in a convoy (trucks drive in a line at nearly the same speed).
- A degree of simplification is provided by the fact that trucks have a more limited speed range than cars.
- The commercial deployment of trucks means that the focus during configuration is placed more on economy than on sports and comfort. Fuel consumption and wear must be at least as good with ACC as with an average driver.

As a general principle, the same type of ACC system can be used for buses, trucks and tractor units. The requirements with regard to drive and braking systems, manual, semi-automatic or fully automatic transmissions are also very similar in buses and trucks. Only with the configuration of the system are there heightened requirements in buses with regard to comfort.

System design

The system architecture of ACC for commercial vehicles is barely different at all from that of ACC for passenger cars. However, the range of the sensors can be shorter owing to the lower speeds involved. The environmental and service-life requirements imposed on the components in this respect are much higher.

ACC control is configured in commercial vehicles for optimum consumption and wear performance. Thus, for example, the service-brake system is activated only when the available retarder is no longer able to decelerate the vehicle in the manner requested by the ACC controller. Brake wear caused by ACC is therefore for the most part at the same level as that caused by an average driver. The same applies to fuel consumption, in which case a positive effect compared with an average driver can also be discerned thanks to ACC.

As well as these ACC systems, there are for commercial vehicles also predictive ACC systems which, on the basis of route-topology information that is learned or stored in maps, optimize the driving speed in such a way as to achieve the lowest possible fuel consumption. The systems achieve this for example by no longer accelerating ahead of humps in the road or on downhill stretches with a subsequent uphill gradient by better utilizing the kinetic energy through increased speed. The proven savings are, even when compared with good drivers, in the range of 5 to 10%.

In some countries, e.g., the USA and Canada, there are even ACC systems which on account of the simpler brake architecture influence solely the engine torque or the continuous braking torque. The driver must therefore intervene manually more often.

ACCplus

First generation ACC systems had limitations in their range of functions resulting from the limited functionality of sensors and actuators. The limited object-sensing range and the limited horizontal resolution capacity only permitted operation above 30 km/h. Therefore ACC could not

initially be used down to low speeds and at a standstill. The ACCplus system (in series production since 2009) has a further-developed radar sensor with wider angular coverage ($\pm 15^\circ$) and improved detection properties, and thus permits braking to a standstill and restarting by driver intervention. Pressing the accelerator pedal within a predetermined time limit is sufficient to reactivate the system.

Thanks to its greater reliability in destination selection and its even better ability to detect objects at close range, ACC can now also be used in traffic-jam situations.

ACC with low-speed following

During low-speed following (ACC Stop & GO, ACC LSF, Low Speed Following), the data from the long-range radar sensor is combined with the data from the medium or short-range sensors (short-range radar sensors or ultrasonic sensors) in order to provide an exact measurement of objects in front of the entire vehicle.

It operates in a speed range of 0 to 200 km/h, brakes the vehicle to a standstill, and automatically restarts within a predetermined time limit.

Sensor-data fusion with a video camera

Object measurement and object classification can be performed by means of sensor-data fusion with a video camera. This enables robust control over the vehicle with regard to stationary objects.

By combining with video sensor technology, it will be possible for low-speed following to perform full linear guidance at all speed ranges and also in urban traffic in the future (FSR, full speed range). ACC has also provided the basis for developing assistance systems which automatically intervene in critical driving situations to avoid accidents or to mitigate the consequences of accidents. Further developments are geared towards automatic evasive maneuvering by automatic steering intervention.

Current ongoing developments

Electronic horizon

The quality of the ACC function is being improved based on digital maps. The navigation system determines the position of the vehicle and estimates the expected path that the vehicle will travel (most probable path, MPP). A wide variety of predictive information is provided along this path by accessing digital navigation maps (electronic horizon). Examples of this include the road class, the geometric shape of the road, expressway exits and on ramps, speed limits and the gradient of the road. Manufacturer-specific protocols or the ADASIS standard [4] using CAN bus are used to provide the electronic horizon to the ECU.

The ACC system can access this information to improve its function. For example, the predictive course of the road can be used to more reliably assign oncoming radar specifically to a lane (reducing adjacent lane interference). The acceleration of the vehicle can be prevented when approaching an expressway exit if an oncoming radar object is lost when switching to the deceleration lane. The set speed can be reduced automatically before coming to a very tight curve.

In the future, the increased enhancement of the digital map with data and improvement in data quality will enable innovative assistance functions in combination with the ACC system, including predictive, fully automated specification of the set speed. The driver no longer has to enter the intended speed manually; the ACC system determines it automatically by communicating with the navigation system.

This allows the ACC system to implement predictive driving strategies in combination with the engine control unit, which minimize CO₂ emissions. If the ACC "sees" a speed limit or curve in advance via the electronic horizon, the vehicle can roll or coast to it with optimal fuel consumption. The gradient of the road is also taken into account when initiating the rolling or coasting procedure.

Networking with the cloud

The higher the ACC function's degree of automation, the greater the requirements are on the timeliness, precision and reliability of the data in the electronic horizon. To increase the data quality of the digital map, the vehicle itself will contribute to recording street environment data using its sensors. The function: Information such as traffic signs or the cornering speed are recorded by the vehicle's sensors, supplemented with data from the navigation system (e.g. position) and sent to the server (cloud) via mobile communications. In the central server, the incoming signals from many vehicles are processed, compiled and prepared for retrieval. The server information can be requested by vehicles with navigation systems. This ensures that the most recent information is always available. The incoming data from the server is applied to the local navigation map as new knowledge and provided to the ACC system immediately via the electronic horizon.

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Lane assistance

Drifting from the lane unintentionally frequently leads to serious accidents. It is caused for the most part by the driver being distracted or tired (e.g. microsleep). Lane departure warning (LDW) is designed to help avoid such accidents by detecting the lane markings ahead and warning the driver if there is a danger of a lane marking being crossed without the turn signal having been activated. The lane-keeping support system (LKS) also actively intervenes in vehicle guidance.

Assistance systems that afford the driver further lateral-guidance support on expressways/interstates with roadworks (roadworks assistant) or in urban traffic (bottleneck/constriction assistant) are currently in development.

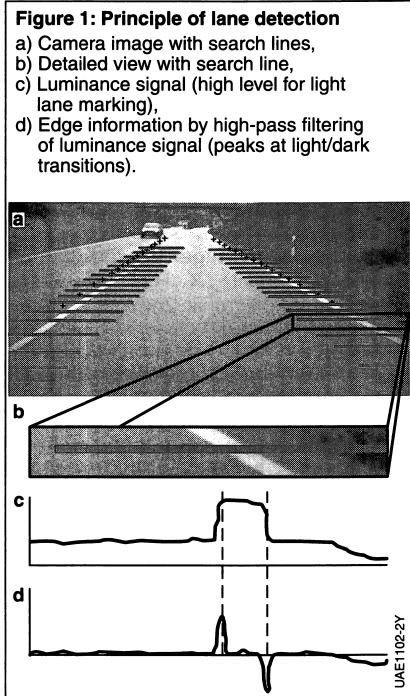
Lane departure warning

Lane detection

Lane-departure warning systems use video cameras to detect the lanes ahead of the vehicle and can have both mono and stereo video designs. A stereo video sensor offers advantages when the road surface exhibits more pronounced gradients, as is typical for example of many country roads. Here the stereo video sensor helps to estimate the surface profile. Knowledge of the surface profile simplifies in the next stage the detection of lane markings and extends the detection range. There are no advantages for lane detection on expressways/interstates as here only slight changes in the surface profile are permitted by statutory requirements. In good weather conditions and with good lane markings, the range is in the region of up to 100 m.

Figure 1 shows the principle of video-based lane detection. The image-processing system searches for lane markings by analyzing differences in contrast between the road surface and the lane markings. Figure 1a shows the camera image with search lines, Figure 1b shows a detailed view. The crosses in Figure 1a mark the course of the lane which have been calculated by the image-processing computer. In order to detect a line, the luminance signal (brightness) inside the search line is analyzed (Figure 1c). The limits of the lane markings are detected by high-pass filtering (Figure 1d). The lane covered by the system vehicle can be detected on the basis of the limiting lane markings. A brief absence of lane markings can be compensated for in the currently available systems. No lane assistance can be offered if the markings are absent over wide areas.

Research is currently being conducted into systems which are intended to detect the roadsides even without markings on the basis of the surface structure and color. The attributes of the last road driven on are also utilized as models. When such systems are market-ready



in a few years, lane-assistance systems will also be available on unmarked roads.

Driver warning

A warning for the driver can be derived on the basis of the detected lanes in the event of the vehicle drifting out of lane. Different forms of warning are conceivable here. The first systems used an acoustic warning from the vehicle speaker in the form of a warning sound or "rumblestrip rattling"; a stereo sound can additionally convey a direction here. However, the systems that have become the most widely used since then feature warning the driver via the haptic sensory channel by vibrating the steering wheel or subjecting the steering to a slight counter-torque. The advantage of issuing the warning through the steering wheel lies in the driver directly associating the danger with the movements on the steering wheel.

Regulations and standards

Together with the mandatory introduction of the automatic emergency-braking system for heavy commercial vehicles (8 t and upwards) the Lane Departure Warning System (LDWS) has been prescribed for this vehicle class in the EU (European Union LDWS Regulation (EU) 351/2012 [1]). Here too the introduction was conducted incrementally from 1 November 2013 initially for vehicles to be newly homologated and from 1 November 2015 for all new vehicles brought onto the roads.

Lane-keeping support

Supporting interventions

Lane-keeping support is a functional enhancement of lane departure warning in that it not only warns the driver against drifting unintentionally from the lane, but also actively supports him in maintaining course. If the vehicle drifts too far from the lane, lane-keeping support makes a course correction, either by means of an active steering intervention or an asymmetrical braking intervention. In this way, the system supports the driver in keeping his vehicle on course and at the same time helps to increase road safety by avoiding accidents caused by drifting unintentionally from the lane.

However, lane-keeping support itself cannot assume full lateral guidance of a vehicle, but is instead intended to support the driver in maintaining course. The system does not relieve the driver of his responsibility to follow and react to the traffic conditions attentively and to drive the vehicle consciously and deliberately. A system intervention can be overridden by the driver at any time.

To prevent misuse, the lane-keeping support system is fitted with a device which monitors whether the driver has both hands on the steering wheel and is actively steering the vehicle. If the driver is driving with no hands, an instruction is promptly issued to the driver to take control of the vehicle and the assistance afforded by lane-keeping support is terminated with an accompanying visual or acoustic warning.

Applications

Lane-keeping support is designed primarily for use on expressways/interstates and well developed highways. Like lane departure warning, lane-keeping support is dependent on detecting lanes ahead of the vehicle. Short-term failures in lane detection, caused for example by hidden or faded lane markings, are compensated for by the system. However, lane-keeping support is deactivated if no lane information is received for an extended period of time.

Roadworks assistant

Applications

Roadworks assistant and bottleneck/constriction assistant are further developments of lane-keeping support. In addition to lane markings, these systems also detect raised objects and obstacles and take them into consideration in lateral guidance.

The roadworks assistant supports the driver in negotiating roadworks on expressways/interstates and thus extends the lane-keeping support system to include this special scenario [2].

Types of support

The type and the extent of support provided can vary greatly. The system can run through all the stages of a cascade of intervention, from the visual, acoustic or haptic warning right up to interventions in vehicle guidance. An intervention in vehicle guidance can involve interventions both in the lateral vehicle dynamics (steering torque or asymmetrical braking intervention) and in the longitudinal dynamics (deceleration). Automatic deceleration can help to keep the vehicle in lane if it drives too fast into a roadworks chicane.

Detection of lane restrictions

Because roadworks are more complex in their structure than the typical expressway/interstate environment, the roadworks assistant detects roadworks-specific lane restrictions (traffic beacons, cones, safety barriers) in addition to the regular lane markings. The sensor functions are typically performed by a front-end stereo video camera and side-mounted ultrasonic sensors. These sensors enable the system to distinguish between static objects (e.g. roadside structures) and dynamic objects (e.g. vehicles). In this way, the system can take the necessary collision-avoidance action in the event of lane constrictions at roadworks caused by traffic in neighboring lanes. This in turn affords the driver support to suit the situation as he or she drives through expressway/interstate roadworks and as a result offers the best support possible for maintaining a sufficient safety distance.

Bottleneck/constriction assistant

Applications

The bottleneck/constriction assistant extends the roadworks assistant with regard to the typical speed range in urban areas (0 to 60 km/h) and with regard to the supported radii of bends. Collision-avoiding steering assistance is offered in urban bottlenecks/constrictions accordingly.

Functionally negotiable bottlenecks/constrictions can also be caused by objects traveling in the same direction or by oncoming objects. The bottleneck/constriction assistant provides automatic steering interventions so that a sufficient safety distance from side obstacles is maintained when passing through tight spaces (bottlenecks, constrictions). It also ensures that an early warning is issued to the driver and an automatic brake intervention is effected if there is not enough space for the vehicle to be able to pass.

As with lane-keeping support, the intensity of the steering and brake interventions is restricted. The interventions can be easily overridden by the driver so that potentially motiveless interventions remain fully non-critical and thus without consequences.

The feasibility of the functional idea was demonstrated by the implementation of an in-vehicle prototype as part of the publicly funded UR:BAN project concluded in 2016 [3]. The prototype's system response in a typical urban scenario is shown in a video in [4]. The bottleneck/constriction assistant is currently in the advance-development stage. The date of a series launch is still open.

Environment detection

A functional requirements analysis reveals that a forward-mounted stereo video camera and alternatively side-mounted ultrasonic sensors or monocular video sensors must be used. The stationary environment and moving objects (those traveling in the same direction and oncoming objects) must be represented within the framework of environment modeling. An occupancy grid presents

itself for the stationary environment. An occupancy grid is a metric grid of the vehicle's environment. Typical cell sizes range between 10 cm and 20 cm. If an object exists in the system vehicle's surrounding environment, the affected grid cells are marked as occupied. Dynamic objects are pictured by way of object models with various function-related attributes (position, width, length, speed, and acceleration).

Evaluation of the traffic situation

The situation analysis must make an assessment of the collision risk in accordance with the planned trajectory of the vehicle and the moving objects, and incorporating the stationary environment. Criticality measurements which are used in the function module to detect critical situations where action is required are typically calculated for this purpose. A typical criticality measurement of this type is the braking-time reserve (also called "time to brake"), which specifies how much time the driver still has to avoid, through a self-initiated brake intervention, a collision for example in an unpassable bottleneck/constriction. If the driver is no longer able to react (i.e. the braking-time reserve is zero or negative),

a collision-mitigating system response is authorized.

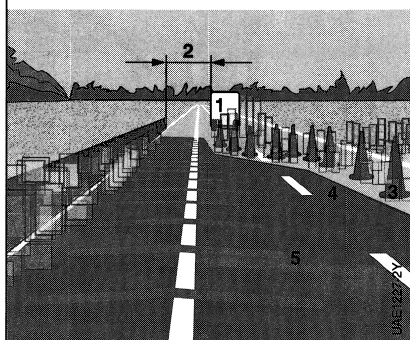
Response model

The function module checks, aside from the criticality measurements mentioned, that the system limits are observed (e.g. whether the maximum supported bend is exceeded) and activates where necessary steering and brake assistance or issues an early warning to the driver.

Figure 2 visualizes some central calculation results by the bottleneck/constriction assistant in a test scenario with a passable bottleneck/constriction while using typical test equipment (safety curbs, cones, balloon car). The rectangles represent detected collision-relevant objects. The gray area (in the graphic on the left of the pictured boundary line) codes the available road width in the bottleneck/constriction. The stripes on the level show the predicted corridor for the vehicle.

Figure 2: Bottleneck/constriction assistant – visualization of calculation results

- 1 Inflatable obstacle (balloon car),
- 2 Bottleneck/constriction,
- 3 Collision-relevant objects (e.g. cones, safety curbs),
- 4 Available road width,
- 5 Predicted corridor.



References

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Lane-change assistant

The number of passenger-car accidents caused by inappropriate lane changing was in the past years regularly in the range of between 6 % and 8 % [1]. Here, the incidence of accidents is mainly centered on highways and expressways/interstates. Drivers initiate a lane change and fail to notice other road users either next to or behind their vehicle. In the first case, the other road users are outside the field of vision of the side mirrors (blind spot, see Figure 1). On expressways/interstates the colliding vehicles are typically driving at similar speeds, i.e. are traveling parallel or slowly overtaking. In the second case, a lane change is made in front of a vehicle that is approaching from the rear at high speed. A typical outcome here is a rear-end collision.

Subfunctions which can address the two types of accident mentioned are described in the following. The functions described are available for trucks and motorcycles as well as for passenger cars. The principle of operation is the same, regardless of the vehicle type.

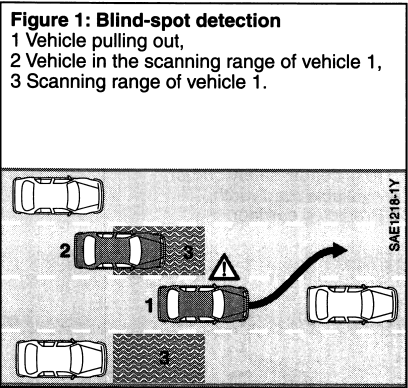
Blind-spot assistant

The blind-spot assistant helps to avoid the first type of accident mentioned.

Environment detection

There are various sensor concepts, differing in terms of costs and performance. In order to avoid this type of accident, only the area directly next to or just behind the system vehicle is relevant. What all the sensor concepts have in common is that the range to the rear extends only a short distance beyond the rear end of the vehicle.

There are systems that utilize the ultrasonic sensors (also used for the parking aid) at the rear corners of the vehicle. As a result, small objects (e.g. scooters) which are situated directly next to the system vehicle cannot be measured, since these are outside the ultrasonic sensor's field of vision. Another solution available on the market utilizes mono cameras in the side mirrors. In a third variation, short-range radars to the sides are used. In the last two cases mentioned



even smaller objects at the sides of the vehicle can be detected by sensors. It is to be noted that the sensors mentioned can be used again by the vehicle manufacturers in a value-added approach for a variety of functions (e.g. parking aid, turning assistance, integral safety).

Sensor-related challenges arise in driving maneuvers that involve high transverse dynamics (turning operations). Here the manufacturers typically set system limits (e.g. thresholds for lateral acceleration, yaw rate, radius of curve which when exceeded deactivate the system) in such a way that incorrect object measurements and consequently false system warnings are avoided.

Response model

The following warning cascade will run if the sensor system detects a vehicle in the neighboring lane.

In a first stage, only slightly perceptible driver information is provided in the form of a side-specific activation of visual symbols or light elements in the side mirrors. If the driver additionally signals a lane-change request (e.g. by activating the direction-indicator lamp or on the basis of the measured driver steering torque on the steering wheel), the visual display can flash, followed by a supplementary acoustic warning or even a slight intervention in lateral guidance. The latter steering intervention can actively prevent or impede the lane change. Automatic steering intervention can be easily overridden and is comparable in terms of intervention intensity with that of lane-keeping support.

Lane-change assistant

As described above, the blind-spot assistant, on account of the limited sensor field of vision to the rear, cannot react to vehicles approaching at high speed from the rear (with the typical outcome of a rear-end collision). Here, the function of the lane-change assistant supplements the range of functions of the blind-spot assistant, i.e. simultaneously monitors the space to the sides of the vehicle as well.

Environment detection

In contrast to the blind-spot assistant, exclusively mid- or long-range radars are used here; these are mounted on a passenger car at the rear corners below the bumper. If a truck is fitted with a lane-change, this is typically positioned under the side mirror.

In particular for passenger cars the radar-antenna radiation pattern is typically set out in such a way that the radar sensor with a smaller radar lobe of low range also covers the area next to the vehicle. The radar sensors use attain a range of up to 100 m to the rear.

Response model

Unlike with the blind-spot assistant, an object prediction is now conducted on the basis of the object list created in environment detection. The system therefore measures whether at a given system-vehicle speed the object approaching from the rear would enter into a critical situation, i.e. would have to brake sharply, if the system vehicle changes lane. The braking-time reserve (time to brake, see Bottleneck/constriction assistant) of the approaching object is determined as the criticality measurement for this purpose. If a lower threshold is undershot (typically <2 to 3 seconds), the lane change is assessed as critical and the escalation cascade passes, as with the blind-spot assistant, into the second stage. The actual response model now corresponds to that of the blind-spot assistant.

Further developments

Automation of the lane-change operation – particularly on expressways/interstates – is conceivable with the above-mentioned lane-change assistant. Such systems are currently in development.

Here the system indicates to the driver the possibility of a safe lane-change maneuver provided the system vehicle is following another slower vehicle. The driver enables the maneuver and can gently place his or her hands on the steering wheel. The system performs the lane change automatically. In combination with Adaptive Cruise Control (ACC) the system would speed up the vehicle and then after the overtaking operation

is completed get the vehicle back in lane in front of the overtaken vehicle.

Since the radar sensor monitors the traffic behind the vehicle, such a maneuver can only be initiated if there is no risk of a side collision. This significantly increases overall safety. Most of the accidents that currently occur due to driver error when changing lanes could thereby be avoided.

References

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Emergency-braking systems

Emergency brake assist and automatic emergency braking

A significant number of road accidents are collisions between vehicles driving in the same direction, i.e. rear-end collisions. Driver-assistance systems which can avoid such accidents or at least mitigate their consequences have been in series production for some years now. A simple feature is the brake assistant (see Brake-assistance functions). Systems that use sensor technology to observe and interpret the vehicle's surroundings have a particularly high potential [1]. This enables such a system to make the necessary anticipatory intervention in vehicle guidance in order for example to avoid an accident with emergency braking.

Environment detection

To be able to avoid rear-end collisions, it is necessary to observe the vehicle traveling in front and its movement. If the system detects that a collision is imminent, it can take appropriate action, for example by issuing a warning to the driver or by performing emergency braking.

Various sensors are suitable for observing the vehicle environment. Their range and sensing range constitute an important function-relevant feature. The required look-ahead distance of the sensors is derived above all from the speed range in which the function is to be active. Radar sensors are used predominantly used for long ranges which are required at high driving speeds. Mono and stereo video sensors typically achieve medium look-ahead distances. Lidar sensors can be used for both medium distances and close range.

Several sensors are frequently combined for a automatic emergency-braking system. This offers two advantages: Firstly, the strengths of the individual measurement concepts complement each other, providing for a more accu-

rate measurement of vehicles traveling in front. Secondly, system reliability is enhanced in that possible faults in individual sensors can be detected. In particular, unjustified system responses can be avoided. It is also possible, albeit with a loss in performance, to realize emergency-braking systems which are based merely on the data from a single sensor.

Attributes of objects traveling in front such as position, speed, acceleration, and object size and type are assessed on the basis of the environment-sensor data and taking into account the motion of the driver's own vehicle. These object attributes are then used to evaluate the traffic situation with regard to its criticality.

Evaluation of the traffic situation

Different measures have become established that describe how critical the current traffic situation is, i.e. how probable it is that a collision with a vehicle traveling in front is imminent (criticality measurements). Assumptions regarding the future motion both of the vehicle traveling in front and of the driver's own vehicle are made for this purpose. This is possible since only very short prediction horizons are required for emergency-braking systems. It can be assumed for instance that the driver of the actual vehicle will still try by means of an avoidance maneuver to avoid the collision. Assuming maximum transverse dynamics for this avoidance maneuver, the last possible moment when the driver can still avoid the collision by evasive maneuver can be calculated. The time remaining until this moment is called the "time to steer" (TTS). Similarly, a "time to brake" (TTB) can be calculated, i.e. the time remaining to the driver to still avoid the imminent collision by means of a braking maneuver. The shorter these times, the more critical the traffic situation. There

are many more criticality measurements, e.g. the probability of a collision in the future “time to collision” (TTC). To be able to calculate these, it is necessary to make assumptions about probability distributions for the future motion of the vehicles involved.

Response model

Different system responses can be initiated if a collision is imminent and this is detected when the above-mentioned criticality measurements are undershot. The time sequence of an exemplary system response is illustrated in Figure 1. The following system-response stages exist in standard systems:

Brake preparation

If the probability of an imminent collision increases, the brake system can be prepared by driving-dynamics control (Electronic Stability Control, ESC) in such a way that any subsequent braking (by the driver or by the system) can be effected more rapidly (prefill).

Warning

The driver can be warned in the event of a heightened collision risk. A warning is suitable to force the driver into a tried-and-tested response, especially if he has

not yet recognized the danger. An accident can thus be avoided by the driver himself if the advance-warning time is long enough.

However, when configuring a warning function, it is important not to set the advance-warning time at too long; in such a case the warning would frequently be issued already in easy-to-control, non-critical situations and would thus be perceived to be unjustified.

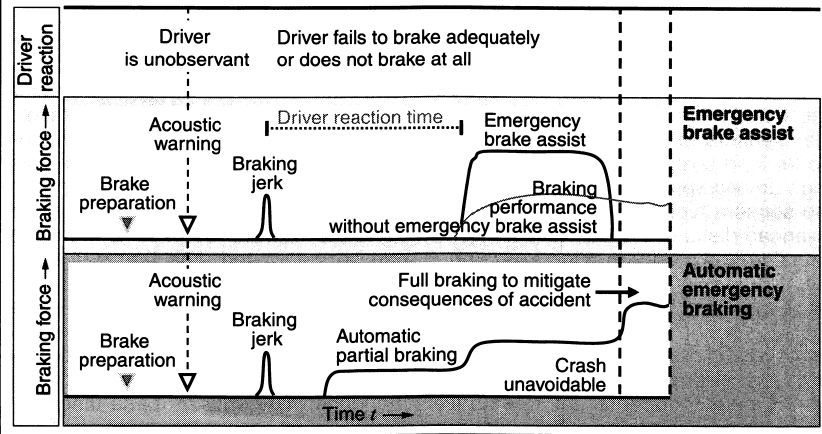
Braking jerk

The braking jerk constitutes a further warning escalation stage. Here the brake system is automatically activated for a brief period and then released again immediately. This has two advantages: Firstly, the driver is warned by haptics of the danger; secondly, the driving speed is already slightly reduced.

Partial braking

Partial braking works along similar lines to the braking jerk. Here a slight deceleration is automatically set, but unlike the braking jerk is not released again immediately.

Figure 1: Braking-response model of Emergency Brake Assist and Automatic Emergency Braking for an unobservant driver who fails to brake adequately or does not brake at all



Brake assistant

Frequently the driver will react to the critical situation by initiating a braking operation that is too weak to avoid the accident. In this event the system can boost the braking force requested by the driver so as to bring the vehicle to a stop in good time before the obstacle and avoid the accident.

Full braking

If the system responses described above are not sufficient or the driver fails to react appropriately to avoid the imminent collision, the above-described criticality measurements do not decrease sufficiently – the situation therefore remains critical. In this case, automatic full braking is initiated at the last moment. A possible criterion for activating emergency braking is for example a “time to brake” which is virtually zero or negative. Automatic full braking will frequently prevent an accident entirely, but at least will greatly reduce the impact speed.

Regulations and standards***Emergency-braking systems for passenger cars***

Since 2014 automatic emergency braking when driving in the same direction has been part of the Euro NCAP assessment (European New Car Assessment Program). Emergency-braking systems are assessed by reference to standardized collision scenarios which are recreated on a test track. Here, both the avoidance of collisions by an emergency-braking system and a reduction of the impact speed are positively assessed. The effectiveness of the emergency-braking system installed in each case finally affects the number of NCAP stars that a vehicle can achieve.

Emergency-braking systems for commercial vehicles

An automatic emergency-braking system (AEBS, Advanced Emergency Braking Systems) has since been prescribed in the EU for heavy commercial vehicles weighing 8 t and upwards (European Union AEBS Regulation (EU) 562/2015, [2]). The introduction was conducted incrementally from 1 November 2013

initially for vehicles to be newly homologated and from 1 November 2015 for all new vehicles brought onto the roads. In a further step the requirements with regard to reducing the speed in respect of moving and stationary targets were tightened from 2016.

Available systems

Various systems are currently available which can significantly reduce speed in critical situations and frequently avoid the collision entirely. However, an automatic emergency-braking system can involve the additional risk of a rear-end impact and in the event of unjustified deployments give rise to acceptance problems. Suitable measures must therefore be taken within the framework of system development to ensure that no unauthorized emergency braking occurs (see “Test and hedging”).

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Intersection assistant

Motivation

Cause of accidents

Around 26 % of all accidents involving injury in Germany occur when crossing intersections and turning [1]. Driver-assistance systems which are designed to prevent this common type of accident are called intersection assistants. This covers safety functions with the aim of avoiding accidents or mitigating their severity. To achieve this, the driver is alerted at an early stage to an imminent accident or an automatic braking of the vehicle is performed.

Environment sensing

Other road users are detected with radar sensors, video cameras or lidar sensors and their distance, speed and direction of movement are determined. The information is processed by the microcomputer of an ECU and evaluated in the form of an object list in software.

Situation assessment

An imminent accident is predicted whereby the future position of the vehicles is predicted from the measured positions and speeds of other road users and the motion status of the driver's own vehicle. In the next step the system checks whether the predicted vehicles coincide, which would correspond to an imminent collision. It is however necessary to take into account in this respect that the measured positions and speeds are invalidated by measuring errors. It is furthermore not known exactly how the vehicles will move in future, i.e. whether they will for example brake or steer. Therefore, when it comes to predicting the situation development, driving maneuvers which would avoid an accident must also be taken into account. The less these avoidance maneuvers are possible, the more critical the situation. The situation where an accident cannot be avoided or can only be avoided with difficulty by means of normal handling is called an acute collision risk.

It is particularly difficult to distinguish between critical and non-critical situations in intersection scenarios as the vehicles have a large freedom of movement in several direction and the turning behavior of the vehicles involved would have to be predicted several seconds in advance. This is almost impossible, especially when the vehicles involved are being driven in a sporty style. For this reason, an imminent accident can only be unequivocally detected just before the collision.

Unauthorized brake interventions must be avoided without fail as firstly they would not be accepted by the driver and secondly they constitute a potential danger to the following traffic. In certain situations, therefore, automatic emergency braking cannot be activated or can only be activated with a delay. Accident prevention is then no longer possible in some circumstances. If, for example, the driver's vehicle is traveling at high speed, an accident-avoiding braking operation would as a rule have to be initiated very early, but this is not possible due to the situational uncertainties and the risk of incorrect deployments.

But even if the system cannot avoid an accident in an individual case, it can mitigate the consequences of the accident through an automatic braking intervention since the impact speed is reduced and the point of impact favorably shifted under certain circumstances.

A distinction is made between the intersection-assistance systems described in the following.

Intersection-assistance systems

Left-turn assistant

Causes of accidents

The left-turn assistant is designed to prevent accidents which happen when turning left in the face of oncoming traffic (Figure 1). The accident is usually caused by the driver incorrectly judging the speed of the oncoming vehicle – the accident perpetrator turns although there is no longer enough time to complete the maneuver.

An imminent left-turn maneuver by the driver can be detected by an evaluation of turn signal, accelerator pedal, and steering angle.

System response

If the turn cannot be made safely due to the approaching oncoming traffic, the driver is warned in an initial stage. If there is an acute risk of collision, automatic braking or start prevention is finally initiated.

To avoid the situation where the vehicle in the event of an incorrect response cannot be moved in a potentially dangerous situation, the driver can override the start prevention by means of a kickdown.

Cross-traffic assistant

Causes of accidents

The cross-traffic assistant is designed to prevent accidents which happen when crossing intersections and turning in the face of vehicles that are themselves crossing (Figure 2). Because passengers

involved in side collisions are much less adequately protected than in head-on collisions due to the lack of crumple zones, the risk of injury is particularly high.

Obscurements/obstructions are frequent causes of accidents as well as distracted and inattentive drivers.

Environment sensing

As with the left-turn assistant, crossing vehicles are detected by environment sensors. Compared to the left-turn assistant, however, the field of vision to be covered is much wider ($\geq 180^\circ$), meaning that generally several sensors which are mounted at the front corners of the vehicle must be used.

System response

If while the vehicle is entering a blind intersection the system detects a crossing vehicle approaching, the driver is alerted in an initial stage to the presence of a potentially dangerous traffic situation (e.g. visually by way of a neutral indication in the headup display). If the driver attempts to enter the intersection even though another vehicle will shortly be crossing the lane and a safe crossing of the intersection is no longer possible, the system prevents the vehicle from moving, for example by cutting the fuel supply or engaging the brakes. As with the left-turn assistant, start prevention can be overridden by means of a kickdown. At faster speeds a

Figure 1: Situation when turning left with oncoming traffic

- 1 Turning vehicle,
- 2 Oncoming vehicle,
- 3 Sensing range of sensor system (e.g. mid-range radar).

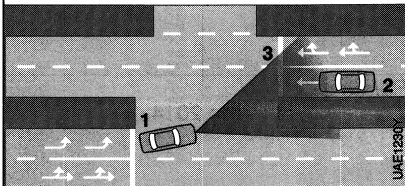
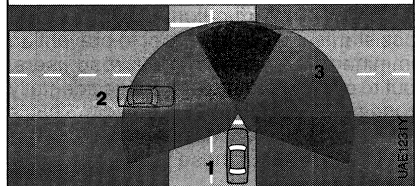


Figure 2: Situation with cross-traffic

- 1 Vehicle driving straight ahead,
- 2 Crossing vehicle,
- 3 Sensing range of sensor system (e.g. mid-range radar, utilizing sensors with widened beam angle).



warning (conspicuous visual or acoustic indications) is issued first in the event of an imminent collision with cross-traffic. If the driver fails to react, the system initiates an automatic brake intervention in the event of an acute collision risk.

Outlook

Because obscurations/obstructions caused for example by parked vehicles are frequently encountered in intersection situations, presumably car-to-car communication (C2C) will also play an important role in the future. Here the vehicles exchange information by radio signal on their position, speed, and steering angle, and can thus detect potential conflicts at an advanced stage and take countermeasures. The position of the vehicle is determined beforehand by satellite positioning. However, extremely accurate locating of the vehicles is required to enable the information from a safety-critical function like the cross-traffic assistant to be used. This is not possible however with the precision of GPS that is currently used by commercially available navigation devices. This is caused by for example atmospheric interference. In the case of Differential GPS (DGPS) a second GPS receiver, whose exact position is known, is used. This generates a correction signal which can be used by other GPS units in the immediate surroundings to correct the interference. Centimeter-perfect locating is thus theoretically possible. However, this system is currently still very expensive and therefore cannot be used for series introduction in vehicles. Furthermore, the GPS receiver must be in direct radio contact with a larger number of satellites, which is often not the case in urban canyons.

Traffic-light and stop-sign assistants

Causes of accidents

Unlike the left-turn and cross-traffic assistants, the traffic-light and stop-sign assistants are designed not to prevent an imminent collision with other road users, but to prevent the driver from accidentally running a red light or a stop sign. This is intended to prevent accidents which happen as a result of these traffic violations.

Environment sensing

A video camera equipped with image-recognition algorithms scans the vehicle environment for traffic lights and road signs (see Road-sign recognition), whereupon their status and their meaning are interpreted. To reduce the risk of erroneous detections, digital maps can be used in which the positions of road signs are marked.

An alternative is offered by car-to-infrastructure communication (C2I). Here, the traffic light for example communicates its status by radio signal to vehicles equipped with special receivers in the surrounding area.

Furthermore, the associated stop line must be detected to enable the system response to be sensibly configured in terms of time.

System response

If the driver is on the point of not stopping at a red light or a stop sign, a warning is issued first. If the driver then fails to react appropriately, the vehicle can also, depending on the system design, be automatically braked.

A sensible response to the yellow phase is only possible if there is still sufficient distance for a comfortable stopping operation or if the remaining duration of the yellow phase is known for example via C2I.

Another type of traffic-light assistance pursues the objective of optimally utilizing the green phases and avoiding unnecessary braking and acceleration phases. Aside from the fluid and comfortable driving style, this is also intended to lower fuel consumption. In this system the traffic lights ahead transmit their traffic-light phase and the time until the phase change to approaching vehicles. The speed at which the next traffic light is reached on green is displayed in the instrument cluster.

References

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Active pedestrian protection

Motivation

The protection of weaker road users, particularly pedestrians, has increasingly taken center stage in recent years. Initially this increased focus resulted in the improvement of passive safety systems for pedestrian protection (e.g. specific design of the vehicle front end to mitigate the consequences of collisions with pedestrians). Now, increasingly, active systems – i.e. systems which clearly act against potential collision – are also going into series production.

Active pedestrian-protection systems react similarly to emergency-braking systems for vehicles traveling in the same direction. However, the environment-sensing requirements are different; this can be identified in an analysis of the frequently occurring types of accident.

Causes of accidents

The majority of pedestrian accidents involve persons who cross the road while the vehicle is driving straight ahead. The pedestrian steps out from the side in front of the car, often from a concealed position (i.e. the pedestrian is initially hidden behind another object).

Another significant number of pedestrian accidents happen at intersections, particularly when vehicles are turning.

Comparison with emergency-braking systems for vehicles traveling in the same direction

System responses

As already mentioned, the system responses for active pedestrian protection are comparable with emergency braking for vehicles traveling in the same direction. The system responds to an imminent collision with a pedestrian with a warning to the driver together with partial and full braking. As pedestrians frequently step out unexpectedly from a concealed position into the road, often only part of the response cascade, i.e. only the partial and full braking for example, is activated.

Environment detection

Pedestrians usually step out from the side into the road. Therefore, when compared with emergency-braking systems for vehicles traveling in the same direction, a wider area in front of the vehicle must be monitored by the sensor system. To make the correct decision on deployment, the sensor system must be able to measure precisely the lateral velocity of pedestrians in particular. Because pedestrians often step out onto the road from a concealed position, sensors must furthermore be able to detect those pedestrians very quickly (i.e., within a few sensor measurement cycles). This is the only way of ensuring a punctual system response (e.g., full braking).

Various sensor configurations for active pedestrian protection are in series production. In this case, both systems which are based on a single sensor and systems which fuse the information from a number of sensors are used. Sensors used are for example mono video cameras, stereo video cameras, or radar sensors.

Situation analysis

To assess the traffic situation, assumptions must be made about the future movement of the road users involved – i.e., here that of the pedestrian and of the driver's own vehicle. In this way, the system can calculate whether an imminent collision situation can still be averted by the driver or whether an activation of automatic emergency braking is necessary. This prediction is performed in all emergency-braking systems (e.g., emergency-braking systems for situations with vehicles driving in the same direction), but is particularly challenging in the case of active pedestrian protection. Pedestrians can very abruptly stop in their tracks, start to run, or change direction. These movement possibilities must be taken into account in the system in order to avoid unauthorized system interventions. For example, so as not to

risk a rear-end collision with the following traffic, the system is not permitted to initiate emergency braking for a pedestrian who steps out onto the road but then stops in time.

Assessment standards

Since 2016 automatic emergency braking for pedestrians has been part of the Euro NCAP assessment (European New Car Assessment Program). Emergency-braking systems are assessed by reference to standardized collision scenarios which are recreated with dummy pedestrians on a test track. Three basic collision scenarios are tested, with the tested vehicle driving straight ahead at different speeds in all the cases:

- an unconcealed pedestrian crossing from the opposite side of the road (in right-hand traffic therefore from the left),
- a pedestrian crossing from the same side of the road (in right-hand traffic therefore from the right), and
- a pedestrian crossing from behind a parked vehicle.

In the last case the dummy pedestrian is the height of a child. The dummy pedestrians are able to move their legs and thus realistically mimic a real walking pedestrian. This is necessary since the movement of the legs is sometimes an important attribute in classifying the detected object as a pedestrian, without which automatic emergency braking would not be initiated. Radar sensors detect for example the leg movement of pedestrians via the micro-Doppler effect. This is characterized by a minimal oscillation of the pedestrian's measured speed signal.

High-beam assistant

Function

The high-beam assistant automates the process of switching between low beam and high beam. It detects vehicles driving in front and oncoming vehicles and automatically switches the high beam on or off to suit the traffic situation. This significantly increases safety and comfort when driving at night, mainly on highways and expressways.

Motivation

Statistics show that people are exposed to a significant risk of being involved in a serious accident when driving at night. Tests further show that the average driver typically engages the high beam between 5 % and 19 % of his journeys at night and drives on low beam for the rest of the time, even though the option exists to engage the high beam. Some drivers do not engage the high beam at all and continuously drive on low beam. A system with high-beam assistant would activate the high beam in more than 30 % to 40 % of the distance driven at night (more than twice as often as a typical driver activating manually), thereby improving significantly the illumination of the road compared with the low beam. The figures from the statistics are very much dependent on the traffic density – the lower the density, the greater the use of the high beam. It has also been established that fatigue and lack of concentration causes drivers not to manually turn off the high beam reliably and thus to dazzle other road users.

An automatic system offers a dramatic improvement for all road users. The driver of a vehicle with a high-beam assistant experiences a noticeable reduction of the burden and, thanks to automatic activation, a more frequent improvement in illumination. Automatic deactivation of the high beam ensures that drivers of oncoming vehicles are not dazzled.

System design and function

The system consists of a light-sensitive sensor or a camera, combined with an ECU which controls the headlamp. The camera is either integrated in the rear-view mirror or installed in a standalone sensor assembly on the windshield. The camera detects and distinguishes between vehicles and stationary street lights. The system detects oncoming vehicles up to a distance of 600 m and tail lamps of vehicles driving in front up to a distance of 400 m. The positions of detected objects are transmitted to the headlamp ECU, with the data being transmitted via the CAN bus used in the vehicle. The headlamp ECU calculates from the position data whether an object is in the headlamp's beam range and dazzling can occur. The high beam is automatically deactivated if the sensor system detects an object that can be dazzled. If the sensor system does not detect an object, the high beam is automatically activated. The high beam is deactivated even in the presence of street lights for example in urban areas which the system detects and can distinguish from other objects.

Further developments

In the further development of the high-beam assistance function the camera-controlled "glare-free high beam" will further establish itself in vehicles in the years to come. In response to image analysis of the camera in the face of oncoming traffic or traffic in front, the high beam in these systems is only deactivated in the areas or shaded by screens in which other road users are located. New optical systems are used in the headlamp for this purpose. Most of the high beam can thus remain switched on and contribute to the driver's safety and comfort without dazzling other road users.

Future of automated driving

Long-term goal – autonomous driving

Driving a car can be fun, but can also be tiring or even dangerous. Automated systems such as driver-assistance systems support drivers in difficult driving situations or relieve them of tiresome and monotonous driving tasks.

A trend that has been observed in recent years is the increasing degree of automation of the systems on the market. This trend will continue in the future [1], [2].

Degree of automation

The German Federal Highway Research Institute (BAST) divides driving functions based on the degree of automation into the following categories [3]:

Assisted

The driver permanently performs either longitudinal or lateral guidance. The remaining driving task is performed within certain limits by the assistance system. The driver must constantly monitor the system and be ready at all times to take complete control of vehicle guidance/handling.

Partially automated

The system performs longitudinal and lateral guidance for specific situations or for a limited period of time. The driver must constantly monitor the system and be ready at all times to take complete control of vehicle guidance/handling.

Highly automated

This degree of automation equates to “Partially automated”, but in this case the driver does not have to permanently monitor the system. If the system limits are reached, the driver can be prompted to take control within a certain period of time.

Fully automated

The vehicle performs all the driving tasks for a specific application without the driver having to monitor the system. If the system limits are reached, the system can still establish a safe state without the driver having to intervene.

Autonomous driving

The logical extension of this development is a system that can permanently perform all the driving tasks without the driver having to monitor the system. The driver becomes a passenger and can use the journey time for other activities, such as for example reading, working or even sleeping.

Further applications would include the vehicle independently looking for a parking space (see “Parking and maneuvering systems”), driving to the garage or taking the children to school without a driver actually having to be in the vehicle. Last but not least, it is hoped to reduce the number of accident fatalities in that a computer-controlled system can essentially react faster and more reliably than a person.

This results in an extension of the list published in [3]. Opinions differ as to whether and when autonomous driving will catch on.

Obstacles to automated driving

The idea of driverless driving has been pursued for several decades in numerous research projects [4]. As early as 1986 Professor Dickmanns (University of the Federal Armed Forces, Munich) introduced a "robot vehicle" which was able to drive autonomously on expressways/interstates at speeds of up to 96 km/h. In 1995 Professor Dickmanns' team drove another vehicle from Munich to Copenhagen and back (covering a distance of 1,758 km) with automatic longitudinal and lateral guidance. The system was available for 95 % of the journey time.

In 2004 the US Department of Defense organized the DARPA Grand Challenge (DARPA, Defense Advanced Research Projects Agency), the first competition over a longer distance for autonomous vehicles.

The DARPA Urban Challenge organized in 2007 involved the autonomous vehicles having to perform a range of tasks in quasi-urban traffic in a former air-force base.

As the various research projects have shown, today it is perfectly possible to build an autonomous or at least fully automated prototype vehicle. But before such vehicles can be put into series production, some technical and non-technical obstacles have to be overcome.

At the beginning of 2013 Robert Bosch GmbH announced it would be joining various vehicle manufacturers and other suppliers in working on the technologies that are required for automated driving.

Technical obstacles

The technical aspects involved are, from a functional standpoint, essentially environment detection, understanding of the situation, and the behavior planning derived from them.

Environment detection

With regard to environment detection, all aspects of the vehicle's surroundings as are a matter of course to a human driver must be sensed and detected. These aspects include detecting other road users and detecting the road, obstacles that cannot be driven over, and the traffic infrastructure (e.g. road markings, road signs and traffic lights).

Understanding of the situation

In the final analysis, the gestures of other road users and traffic police officers must also be interpreted. Both the reliable measurement of all these aspects with close-to-production sensor technology and the processing of the data supplied by these environment sensors with close-to-production ECUs are currently still stretched to their limits.

Behavior planning

A further functional challenge is to derive appropriate actions (behavior planning) in real time. Traffic situations are often highly complex, particularly in urban environments, due to the fact that a multitude of road users, traffic regulations and special situations has to be taken into account. Initial prototype systems are already addressing the urban sphere, e.g. in the low speed range. These systems are however not yet available in production vehicles.

Outlook

With the inexorable advances in development (e.g. with increasing computing capacity, powerful learning algorithms) it appears that these functional obstacles can be surmounted in the foreseeable future.

As for a further technical obstacle, the validation of functional reliability, there is as yet no solution close to hand: A fully automated vehicle naturally may not jeopardize its occupants or other road

users in any situation through failures/faults. The failure rate will therefore have to satisfy extremely stringent requirements for a series-production launch. To ensure this, many millions of kilometers would have to be completed in test drives, which is currently not economically feasible.

Legal obstacles

Finally, there are also legal (non-technical) obstacles that need to be removed. It is unclear for instance who is liable for the damage/injury caused by a fully automated vehicle when the driver no longer has responsibility for vehicle handling.

Aside from the question of liability, highly and fully automated driving functions in public traffic are currently not legal in many countries. Until the start of 2016, according to the Vienna Convention on Road Traffic of 1968, the following requirements were mandatory in Germany and in many other countries around the world: "Every driver shall at all times be able to control his vehicle or to guide his animals" and "Every driver of a vehicle shall in all circumstances have his vehicle under control so as to be able to exercise due and proper care and to be at all times in a position to perform all the manoeuvres required of him".

This meant that the driver may not relinquish his responsibility for vehicle guidance and control and must at least monitor the automated driving function. This has since been adapted and consequently systems for automated driving are now permitted if they can be stopped at all times by the driver.

But there are also countries where this Convention is not valid. It has not been signed or ratified by the USA, for example. However, that country is covered by other regulations and provisions such as, for example, the Geneva Convention on Road Traffic of 1949. Overall, it can be said that the legal situation worldwide is very inconsistent.

Stages on the road to autonomous driving

In view of the obstacles mentioned, it is sensible not to introduce autonomous driving (some time) all at once, but instead to proceed in stages. In other words, to put into series production initially systems with a lower degree of automation – for example partially automated systems – or alternatively to restrict the situations considered by the system accordingly (see road map, Figure 1). Sensible restrictions or situations which can be kept under control more easily are for example

- expressway/interstate situations, due to the more simply structured and less complex environment,
- traffic-jam, parking and maneuvering situations, since they typically occur in the low-speed range, the sensors involved only need to have a short range, and the vehicle can be brought to a stop very quickly and with only a minimal stopping distance.

Combinations are naturally also conceivable, such as the traffic-jam pilot described in the next section.

Development of assisting driving functions

Assisting driving functions such as adaptive cruise control (ACC), lane-keeping support, and parking assistant have been established on the market for some years now. And also partially automated functions such as the traffic-jam assistant are now available on the market. Here the system performs lateral and longitudinal guidance completely in traffic-jam situations. At low speeds the driver does not have to keep his hands on the steering wheel, but does have to monitor the system and intervene if necessary. Systems which are also available at higher speeds are comparatively new. This system is also expected to be further developed in the near future for traveling at higher speeds.

The expressway/interstate assistant assumes at typical expressway/interstate speeds longitudinal and lateral guidance and also automatically performs lane changes, e.g. Tesla "Autopilot" as a combined system of ACC and lane-keeping support. But ultimate responsibility remains with the driver. He must monitor the system so that he can intervene at any time.

One of the first fully automated functions that is expected is the traffic-jam pilot, which assumes full responsibility for vehicle handling/guidance in traffic jams. To realize the follow-on expressway/interstate pilot, it is necessary to provide the emergency stop subfunction, which in an emergency can bring the vehicle to a safe stop on the hard shoulder (emergency lane). Unlike the expressway/interstate assistant, the expressway/interstate pilot assumes responsibility for vehicle handling/guidance. The driver can perform secondary activities, but must where necessary be able to take over the driving task from the system within a maximum on ten seconds.

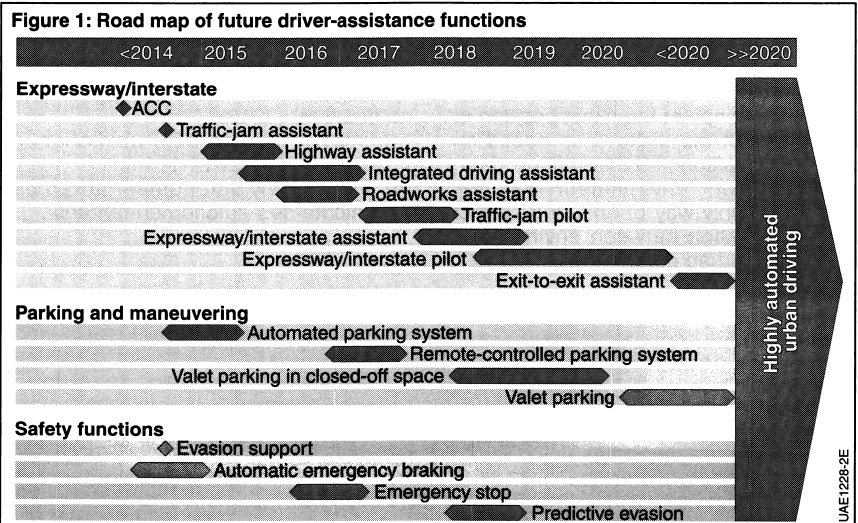
On top of the expressway/interstate functions, the parking and maneuvering functions are also subject to ever-increasing automation. Systems which

drive the vehicle under fully automated conditions under human supervision into a parking space are already available. Still in development, on the other hand, is the valet-parking function, which also searches for a free parking space and performs the parking maneuvers in parking garages or parking lots. The driver can leave his vehicle in the entrance area and then pick it up again later at reception (see "Parking and maneuvering systems").

Because traffic complexity is at its greatest in urban environments, an automated system is subject to particularly high requirements.

Long-term goal – fully automated driving

The logical extension of development is a fully automated vehicle that can take the passengers from door to door like a taxi. Such fully automated systems are also already in development. They are, on account of the absence of driver supervision and thus the absence of a human fallback level, based on a completely different system architecture from classic driver-assistance systems.



Hence fully automated systems must have a redundant design. As well as a failsafe power supply for safety-critical system components and redundant actuators (e.g. steering intervention by power steering or asymmetrical ESC intervention), redundant sensor concepts must be used. The aim is thus to compensate for known shortcomings in the individual sensors. For example, a video sensor as an individual sensor can be dazzled by bright sunlight. A redundant sensor concept is based accordingly on the combined use of sensors that use independent measuring principles (e.g. radar, video, and lidar), but also overlap with regard to their sensing range.

In addition, a new central system component is introduced in fully automated systems with high-precision digital maps. This is required to provide information for representing the surrounding environment which cannot be measured with environment sensors (e.g. course of a road after the bend/curve).

Another new component is the behavior planner, which assumes the job of tactical maneuver planning which was previously performed by the human driver. Examples are the recognition of the need for a lane change, a slipping-in maneuver or an overtaking maneuver, to name just a few.

Exact vehicle locating is necessary to enable the data supplied by the environment sensors to be correctly associated with the digital map. The purpose of locating is to pinpoint the exact position of the vehicle in the digital map based on the GPS position, vehicle-motion data, and prominent environment features. This is the only way of ensuring correct data association between environment sensors and map data.

As well as the pure measurement of stationary and moving objects in road traffic, a fully automated system must be able to understand and utilize all the paths of communication between road users (e.g. gestures and eye contact with a pedestrian on a zebra crossing, hand signals by cyclists, traffic signs carried by police officers or road workers). While technical solutions for communication between vehicles and infrastructure already exist with Car2X, research is currently still being conducted into robust solutions to gesture recognition in road traffic.

The development of these systems is constantly progressing. In a few years these systems will leave their prototype status behind and will be adopted in our everyday lives.

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Abbreviations

A:	
AAS:	Atomic Absorption Spectroscopy
ABS:	Antilock Braking System
ABS:	Acrylnitrile-Butadien-Styrene
ABV:	Antilock braking system (German: Antiblockier- richtung)
AC:	Accessory Control
AC:	Alternating Current
ACC:	Adaptive Cruise Control
ACEA:	Association des Constructeurs Européens de l'Automobile (Association of European Automobile Manufacturers)
ADAS:	Advanced Driver Assistance Systems
ADASIS:	Advanced Driver Assistance Systems Interface Specifica- tions
ADB:	Adaptive Driving Beam
ADC:	Analog-Digital Converter
ADR:	Accord européen relatif au transport international des marchandises Dangereuses par Route (European Agreement concerning the International Carriage of Dangerous Goods by Road)
ADR:	Advanced Digital Receiver
ADR:	Australian Design Rule
AE:	Automotive Electronics
AEB:	Automatic Emergency Braking
AF:	Antiferromagnetic
AFC:	Anti-Friction-Coating
AFS:	Adaptive Frontlighting System
AGI:	Air-Gap-Insulated
AGM:	Absorbent Glass Mat
AHP:	Accelerator Heel Point
AI:	Articulation Index
AKF:	Carbon canister (German: Aktivkohlefaller)
ALB:	Automatic load-sensitive braking-force metering (German: Automatische lastabhängige Bremskraft- regelung)
ALU:	Arithmetic-Logic Unit
AM:	Amplitude Modulation
AMLCD:	Active Message Liquid Crystal Display
AMR:	Anisotropic Magnetoresistive
AMT:	Automated Manual Trans- mission
ANC:	Active Noise Control
API:	Application Programming Interface
API:	American Petroleum Institute
APS:	Active Pixel Sensor
APSM:	Advanced Porous Silicon Membrane
ARLA:	Agente Reductor Liquido de Óxido de Nitrogénio Automotivo
AS:	Air System
ASAM:	Association for Standardization of Automation and Measuring Systems
ASF:	Audi Space Frame (aluminum frame structure of supporting integrated sheet panels from Audi)
ASIC:	Application Specific Integrated Circuit
ASIL:	Automotive Safety Integrity Level
ASM:	Asynchronous machine
ASM:	Trailer control module (German: Anhängersteuer- modul)
ASPIEC:	Automotive Software Process Improvement and Capability Determination
ASR:	Traction control system (German: Antriebsschlupf- regelung)
ASS:	Anti-snow system
ASTM:	American Society of Testing and Materials
ASU:	Automatic interference suppression (German: Automatische Störunter- drückung)
ASVP:	Air Saturated Vapour Pressure
ASW:	Application software
AT:	Advanced Technology
ATF:	Automatic-Transmission Fluid
ATL:	Exhaust-gas turbochargers (German: Abgasturbolader)
AUS:	Aqueous Urea Solution
AUTOSAR:	Automotive Open Systems Architecture

B:

BBA:	Service-Brake System (German: Betriebsbremsanlage)
BCD:	Bipolar, CMOS, DMOS
BCI:	Bulk Current Injection
BCM:	Body Computer Module
BCU:	Battery Control Unit
BDC:	Bottom Dead Center (piston of internal-combustion engine)
BDE:	Gasoline Direct Injection (German: Benzin-Direkteinspritzung)
BEM:	Boundary-Element Method
BETP:	Bleed Emissions Test Procedure
BIP:	Beginning of Injection Period
BIPM:	Bureau International des Poids et Mesures (International Bureau of Weights and Measures)
BLDC:	Brushless Direct Current
BM:	Bus-Minus
BMD:	Bag Mini Diluter
BMS:	Battery Management System
BP:	Bus-Plus
BRM:	Boost Recuperation Machine
BRS:	Boost Recuperation System
BSS:	Byte-Start-Sequence
BSW:	Basic Software
BtL:	Biomass to Liquid
BWC:	Butan Working Capacity
BZ:	Fuel Cell (German: Brennstoffzelle)
BZE:	Battery-Status Recognition (German: Batteriezustands-erkennung)

C:

C2C:	Car-to-Car Communication
C2I:	Car-to-Infrastructure Communication
CAD:	Computer-Aided Design
CAE:	Computer-Aided Engineering
CAFC:	Corporate Average Fuel Consumption
CAFE:	Corporate Average Fuel Economy
CAL:	Computer-Aided Lighting

CAN:	Controller Area Network
CAP:	Compliance Assurance Program
CARB:	California Air Resource Board
CBS:	Combined Brake System
CCD:	Charge-Coupled Device
CCD:	Complex Device Drivers
CCFL:	Cold-Cathode Fluorescence Lamp
CCMC:	Comité des Constructeurs d'automobiles du Marché Commun (CCMC manufacturers committee)
CD:	Compact Disc
CDPF:	Catalyzed Diesel Particulate Filter
CDR:	Clock Data Recovery
CE:	Coordination Engine
CEMEP:	European Committee of Manufacturers of Electrical Machines and Power Electronics
CEN:	Comité Européen de Normalisation (European Committee for Standardization)
CF:	Carbon Fibers
CF:	Conformity Factor
CFD:	Computational Fluid Dynamics
CFPP:	Cold Filter Plugging Point (filterability limit)
CFR:	Cooperative Fuel Research
CFR:	Code of Federal Regulations of the United States
CFV:	Critical Flow Venturi
CGPM:	Conférence Générale des Poids et Mesures (General Conference on Weights and Measures)
CGI:	Compacted Graphite Iron
CGW:	Central Gateway
CHD:	Case Hardening Depth
CI:	Cetane Index
CIP-GMR:	Current-in-Plane GMR
CISC:	Complex Instruction Set Computing
CISPR:	Comité International Spécial des Perturbations Radio-électriques (International Special Committee for Radio Interference)
CLD:	Chemiluminescence Detector
CMMI:	Capability Maturity Model Integration

CMRR:	Common Mode Rejection Ratio	DEQ:	Digital Equalizer
CMOS:	Complementary Metal Oxide Semiconductor	DF:	Dynamo Field
CMVSS:	Canadian Motor Vehicle Safety Standard	DFC:	Data Frame Counter
CNG:	Compressed Natural Gas	DFM:	Dynamo-Field Monitor
CO:	Communication	DFV:	Vapor/Liquid Ratio (German: Dampf-Flüssigkeits-Verhältnis)
COD:	Conversion of Olefins to Distillates	DGL:	Differential Equation (German: Differentialgleichung)
COM:	Communication	DGPS:	Differential GPS
COP:	Conformity of Production	DI:	Direct Injection
CP:	Circular Pitch	DIN:	German Institute for Standardization
CPC:	Condensation Particulate Counter	DIS:	Draft International Standard
CPP-GMR:	Current Perpendicular-to-Plane GMR	DK:	Dielectric Constant (German: Dielektrizitätskonstante)
Cpsi:	Channels per Square Inch	DLC:	Diamond Like Carbon
CPU:	Central Processing Unit	DLP:	Digital Light Projection
CR:	Common Rail	DME:	Dimethyl Ethers
CR:	Chloroprene Rubber	DMOS:	Double-Diffused Metal-Oxide Semiconductor
CRC:	Cyclic Redundancy Check	DMS:	Differential Mobility Spectrometer
CRS:	Common-Rail-System	DMS:	Strain Gages (Strain-gage resistor) (German: Dehnmessstreifen)
CRT:	Continuously Regenerating Trap	DNC:	Dynamic Noise Covering
CS:	Checksum	DOC:	Diesel Oxidation Catalyst
CSC:	Cell Supervisory Circuit	DOHC:	Double Overhead Camshaft
CSM:	Chlorosulfonated polyethylene	DOT:	Department of Transportation (USA)
CST:	Controllo Stabilità e Trazione	DPF:	Diesel Particulate Filter
CtL:	Coal to Liquid	DPMO:	Defects per Million Opportunities
CTS:	Conti Tire System	DRIE:	Deep Reactive Ion Etching
CVD:	Chemical Vapor Deposition	DRM:	Digital Radio Mondial
CVS:	Constant Volume Sampling	DRO:	Dielectric Resonance Oscillator
CVT:	Continuously Variable Transmission	DS:	Diagnostic System
CWS:	Collision Warning System	DSA:	Digital Sound Adjustment
CN:	Cetane Number	DSC:	Dynamic Stability Control
D:		DSM:	Diagnostic System Management
DAB:	Digital Audio Broadcasting	DSP:	Digital Signal Processor
DAC:	Digital-Analog Converter	DSTC:	Dynamic Stability and Traction Control
DAPRA:	Defense Advanced Research Projects Agency	DSTN LCD:	Double layer Super Twisted Nematic Liquid Crystal Display
DC:	Direct Current	DTS:	Dynamic-Trailing-Sequence
DC:	Diffusion Charger	DTM:	Deutsche Tourenwagen Masters
DCT:	Dynamic Coupling Torque	DVB:	Digital Video Broadcasting
DCT-C:	Dynamic Coupling Torque at Center	DVBE:	Dry Vapour Pressure Equivalent
DDA:	Digital Directional Antenna		
DDS:	Digital Diversity System		
DEF:	Diesel Exhaust Fluid		

DVB-C:	Digital Video Broadcasting Cable	EFF:	Designations of Efficiency classes for electrical machines (German: Bezeichnung von Effizienzklassen für elektrische Maschinen)
DVB-H:	Digital Video Broadcasting Handhelds	EFM:	Exhaust Flow Meter
DVB-S:	Digital Video Broadcasting Satellite	EFU:	Activation Spark Suppression (German: Einschaltfunken-unterdrückung)
DVB-T:	Digital Video Broadcasting Terrestrial	EG:	European Community (German: Europäische Gemeinschaft)
DWT:	Dynamic Wheel Torque Distribution	EG:	Self-Steering Gradient (German: Eigenlenkgradient)
DVD:	Digital Versatile Disc	EGR:	Exhaust-Gas Recirculation
DVR:	Compression set	EGS:	Electronic Transmission Control (German: Elektronische Getriebesteuerung)
E:		EH:	Extended Hump
E/E:	Electrics/Electronics	EHB:	Electrohydraulic Brake
EAB:	Electronic shutdown (German: Elektronische Abstellung) (diesel control)	EHD:	Elastohydrodynamics
EAC:	Electronic Air Control	EHF:	Extremely High Frequency
EB:	Electrical steel sheet and strip (German: Elektroblech und -band)	EIPR:	Equivalent Isotropic Radiated Power
EBA:	Emergency Brake Assist	EIR:	Emissions Information Report
EBD:	Electronic Brakeforce Distribution	EIS:	Electrochemical Impedance Spectroscopy
EBS:	Electronic Braking System	EIW:	Equivalent Inertia Weight
EBS:	Electronic Battery Sensor	EKP:	Electric Fuel Pump (German: Elektrokraftstoffpumpe)
EBV:	Electronic braking-force distribution (German: Elektronische Bremskraftverteilung)	ELPI:	Electrical Low Pressure Impactor
EC:	European Community	ELR:	European Load Response
EC:	Electronic Commutated	EM:	Monomode Fiber (German: Einmodenfaser)
EC:	Exhaust closes	EMD:	Engine Manufacturer Diagnostics
ECE:	Economic Commission for Europe	EMP:	Electro-Mechanical Parking brake
ECU:	Electronic Control Unit	EMC:	Electromagnetic Compatibility
ECVT:	Electrical Continuously Variable Transmission	EN:	European Standard
EDC:	Electronic Diesel Control	EO:	Exhaust opens
EDR:	Event Data Recorder	EOBD:	European On-Board Diagnostics
EEC:	European Economic Community	EOL:	End of Line
EEM:	Electrical Energy Management (vehicle electrical system)	EP:	Extreme Pressure
EEPROM:	Electrically Erasable Programmable Read Only Memory	EP:	Epoxy
EEV:	Enhanced Environmentally Friendly Vehicle	EPA:	Environment Protection Agency
EFB:	Enhanced Flooded Battery	EPB:	Electronic Parking Brake
		EPDM:	Ethylene Propylene Diene Monomer
		EPM:	Engine & Powertrain Manager

EPROM:	Erasable Programmable Read Only Memory	FBA:	Parking-Brake System (German: Feststellbremsanlage)
ERBP:	Equilibrium Reflux Boiling Point	FCHV:	Fuel Cell Hybrid Vehicle
ES:	Exhaust System	FC-REX:	Fuel Cell Range Extender
ESC:	Electronic Stability Control	FEA:	Finite-Element Analysis
ESC:	European Steady-State Cycle	FEP:	Fluorinated Ethylene Propylene
ESD:	Electrostatic Discharge	FEM:	Finite-Element Method
ESI:	Electronic Service Information	FES:	Frame-End-Sequence
ESM:	Electrically Excited Synchronous Machine	FET:	Field-Effect Transistor
ESP®:	Electronic Stability Program	FFV:	Flexible Fuel Vehicle
ESR:	Enhanced Seat Belt Reminder	FGR:	Vehicle-Speed Controller (German: Fahrgeschwindigkeitsregler)
ESS:	Energy-Saving System	FH:	Flat Hump
ET:	Rim Offset (German: Einpresstiefe)	FID:	Flame Ionization Detector
ETBE:	Ethyl Tertiary Butyl Ether	FiL:	Function in the Loop
ETC:	Electronic Throttle Control	FIR:	Far Infrared
ETC:	European Transient Cycle	FIR:	Field Information Report
ETFE:	Ethylene-Tetrafluoroethylene	FIS:	Driver-Information System (German: Fahrerinformationssystem)
ETK:	Emulator Probe (German: Emulator-Tastkopf)	FKM:	Forschungskuratorium Maschinenbau
ETN:	European Type Number	FKM:	Fluorocarbon Rubber (German: Fluorkarbon-Kautschuk)
ETRTO:	European Tyre and Rim Technical Organization	FL:	Free Layer
EU:	European Union	FLO:	Fast-Light-Off
euATL:	Electrically Assisted Exhaust-Gas Turbocharger (German: Elektrisch unterstützter Abgasturbolader)	FM:	Frequency Modulation
EUC:	Enhanced Understeering Control	FMCW:	Frequency Modulated Continuous Wave
EUDC:	Extra Urban Driving Cycle	FMEA:	Failure Mode and Effects Analysis
EUV:	Electric Changeover Valve (German: Elektroumschaltventil)	FMVSS:	Federal Motor Vehicle Safety Standard (USA)
EV:	Fuel Injector (German: Einspritzventil)	FPA:	Focal Plane Array
EV:	Electric Vehicle	FPK:	Freely Programmable Instrument Cluster (German: Frei programmierbares Kombiinstrument)
EVAP:	Evaporation	FRAM:	Ferroelectric RAM
EEC:	European Economic Community	FS:	Fuel System
EEA:	European Economic Area	FSN:	Filter Smoke Number
EWIR:	Emissions Warranty Information Report	FSR:	Full Speed Range
F:		FSS:	Frame-Start-Sequence
FAEE:	Fatty acid ethyl ester	FST:	Federal Smoke Test
FAME:	Fatty Acid Methyl Ester	FTA:	Fault Tree Analysis
FAS:	Driver-Assistance System (German: Fahrerassistenzsystem)	FTIR:	Fourier Transform Infrared spectroscopy
		FTP:	Federal Test Procedure
		FW:	Front Wheel

G:

GC:	Gas-Chromatography Column
GCU:	Glow Control Unit
GCC:	Global Chassis Control
GEH:	von Mises yield criterion (German: Gestaltänderungs- hypothese)
GF:	Glass Fibers
GIDAS:	German In-Depth Accident Study
GJL:	Gray Cast Iron with Lamellar Graphite
GJS:	Gray Cast Iron with Spheroid Graphite
GKZ:	Spheroidizing
GLP:	Glow Plug
GMA:	Yaw-Moment Build-Up Delay (German: Giermomentaufbau- verzögerung)
GMR:	Giant Magnetoresistive
GTDC:	Gas-Exchange TDC (top dead center in the exhaust cycle)
GPRS:	General Packet Radio Service
GPS:	Global Positioning System
GSM:	Global System for Mobile Communication
GSY:	Speed Symbol (tires) (German: Geschwindigkeits- symbol)
GtL:	Gas to Liquid
GTR:	Global Technical Regulation
GVW:	Gross Vehicle Weight
GWP:	Global Warming Potential
GZS:	Glow Control Unit (German: Glühzeitsteuergerät)

H:

HBA:	Secondary-Brake System (German: Hilfsbremsanlage)
HC:	Hydrocarbon
HCI:	Hydro Carbon Injection
HCCI:	Homogeneous Charge Compression Ignition
HD:	Heavy Duty
HDDTC:	Heavy-Duty Diesel Transient Cycle
HDEV:	High-Pressure Fuel Injector (German: Hochdruck- Einspritzventil)

HDG:	Light/Dark Boundary (German: Hell-Dunkel-Grenze)
HDK:	Half-Differential Short- Circuiting-Ring Sensor (German: Halbdifferential- Kurzschlussringsensor)
HDP:	High-Pressure Pump (German: Hochdruckpumpe)
HDV:	Heavy-Duty Vehicle
HDPE:	High-Density Polyethylene
HED:	High-Efficiency Diodes
HEV:	Hybrid Electric Vehicle
HF:	High Frequency
HFM:	Hot-Film Air-Mass Meters
HFRR:	High-Frequency Reciprocating Rig
HiL:	Hardware in the Loop
HLDT:	Heavy Light-Duty Truck
HLM:	Hot-Wire Air-Mass Meters
HMM:	Homogeneous Lean
HNBR:	Hydrogenated Nitrile Butadiene Rubber
HNS:	Homogeneous Numerically Calculated Surface
HSLA:	High Strength Low Alloy
HSV:	High-Pressure Switching Valve
HTD:	High Torque Drive
HTHS:	High Temperature High Shear
HUD:	Head-Up Display
HV:	High Voltage
HVA:	Hydraulic Valve-Clearance Compensation
HWL:	Urea/Water Solution

I:

IC:	Intake Closes
IC:	Integrated Circuit
ICA:	Integrated Cruise Assist
ICP-OES:	Inductively Coupled Plasma Optical Emission Spectrometry
ICC:	Integrated Chassis Control
ICE:	Intercity Express
ICM:	Integrated Chassis Manage- ment
ID:	Identifier
IDF:	Integrated Collision Detection Front
IDI:	Indirect Injection
IEC:	International Electrotechnical Commission

IEEE: Institute of Electrical and Electronics Engineers
IF: Intermediate Frequency
IGBT: Insulated Gate Bipolar Transistor
IGES: Initial Graphics Exchange Specification
IHU: Integrated Head Unit
IHU: Internal High-Pressure Forming (German: Innenhochdruckumformung)
IIR: Isobutene-Isoprene Rubber
ILSAC: International Lubricants Standardization and Approval Committee
I/M: Inspection and Maintenance
IMA: Injection-Quantity Compensation (German: Injektor-mengenabgleich)
IMC: Integrated Magnetic Concentrator
IO: Intake Opens
IP: Internet Protocol
IR: Infrared
IR: Individual Control (ABS) (German: Individualregelung)
IRHD: International Rubber Hardness Degree
IRM: Individual Control, Modified (ABS) (German: Individualregelung modifiziert)
IS: Ignition System
ISM: Industrial, Scientific and Medical
ISO: International Organization for Standardization
IT: Information Technology
ITDC: Ignition TDC (top dead center in the power cycle)
ITO: Indium Tin Oxide
ITSEC: Information Technology Security Evaluation Criteria
ITU: International Telecommunications Union
IUC: In Use Compliance
IUMPR: In-Use Monitor Performance Ratio
IUPR: In-Use Performance Ratio
IUPAC: International Union of Pure and Applied Chemistry

J:

JAMA: Japan Automobile Manufacturers Association
JASPAR: Japan Automotive Software Platform Architecture
JFET: Junction-gate Field-Effect Transistor

K:

KAMA: Korea Automobile Manufacturers Association
KBA: Federal Road Transport Office (German: Kraftfahrt-Bundesamt)
Kfz: Motor Vehicle (German: Kraftfahrzeug)
KOM: Motor Bus (German: Kraftomnibus)
KP: Critical Point (German: Kritischer Punkt)
KTL: Cathodic Deposition (German: Kathodische Tauchlackierung)
KTS: Diagnostics Hardware Small Testers (German: Diagnostics Hardware Kleintester)
KW: Short Waves (German: Kurzwellen)
KW: Crankshaft (German: Kurbelwelle)

L:

LAC: Load Adaptive Control
LAN: Local Area Network
lb: pound
lbs: pounds
LCD: Liquid Crystal Display
LCV: Light Commercial Vehicles
LDR: Light-Dependent Resistor
LDT: Light-Duty Truck
LDV: Light-Duty Vehicle
LDW: Lane Departure Warning
LDWS: Lane Departure Warning System

LED:	Light-Emitting Diode	M:	
LEV:	Low-Emission Vehicle	M+S:	"Mud and Snow"
LF:	Low Frequency	MAG:	Active-Gas Metal-Arc (German: Metall-Aktivgas)
LGS:	Linear Equation System (German: Lineares Gleichungssystem)	MAC:	Message Authentication Code
LI:	Load Index (tires)	MAMAC:	MOST Asynchronous Medium Access Control
Lidar:	Light Detection and Ranging	MB:	Mercedes Benz
LIF:	Alternator Liquid Cooling (German: Lichtmaschine Flüssigkeitskühlung)	MCAL:	Micro-Controller Abstraction Layer
LIN:	Local Interconnect Network	MCD:	Measurement, Calibration and Diagnosis
Lkw:	Truck (German: Lastkraft- wagen)	MDPV:	Medium-Duty Passenger Vehicle
LKS:	Lane Keeping Support	MDV:	Medium-Duty Vehicle
LL:	Lower Limit	MEMS:	Micro-Electro-Mechanical Systems
LLDT:	Light Light-Duty Truck	MF:	Medium Frequency
LLK:	Intercooling (charge-air cooling) (German: Ladeluft- kühlung)	MH:	Metal Hydride
LLR:	Smooth-Running Control (German: Laufruheregelung)	MIG:	Metal Inert Gas
LMM:	Air-flow Sensor (German: Luftmengenmesser)	miL:	Model in the Loop
LNG:	Liquefied Natural Gas. Liquid Natural Gas	MIL:	Malfunction indicator lamp
LP:	Low Power	MIL:	Military
LPG:	Liquefied Petroleum Gas	MIM:	Metal Injection Molding
LPTC:	Low Powered Vehicle Test Cycles	MISRA:	Motor Industry Software Reliability Association
LR:	Load Response	MKS:	Multi-Body Simulation (German: Mehrkörper- simulation)
LRF:	Load Response Driving (German: Load Response Fahrt)	ML:	Maturity Level
LRR:	Long-Range Radar	MM:	Multi-Mode Fiber
LRS:	Load Response Start	MMA:	Mean-Quantity Adaptation (German: Mengenmittel- wertadaptation)
LSF:	Low Speed Following	MMT:	Methylcyclopentadienyl Manganese Tricarbonyl
LSG:	Laminated Safety Glass	MNEDC:	Modified New European Driving Cycle
LSI:	Large Scale Integration	MO:	Monitoring
LSU:	Lambda Oxygen Sensor (universal or wideband sensor)	Mol:	Moment of Ignition
LTE:	Long Term Evolution	MOS:	Metal-Oxide Semiconductor
LVDS:	Low Voltage Differential Signaling	MOSFET:	MOS Field-Effect Transistor
LW:	Long waves (German: Langwellen)	MOST:	Media-Oriented Systems Transport
LVW:	Loaded Vehicle Weight (vehicle tare weight plus 300 lb)	MOZ:	Motor Octane Number (German: Motor-Oktanzahl)
LWL:	Optical Fibers (German: Lichtwellenleiter)	MP:	Momentary Pole
LWS:	Steering-Angle Sensor (German: Lenkwinkelsensor)	MPEG:	Moving Picture Experts Group
		mpg:	Miles Per Gallon
		MPP:	Most Propable Path
		MPT:	Multi-Purpose Tire
		MRAM:	Magnetoresistive RAM
		MRR:	Mid-Range Radar
		MSE:	Motronic Small Engines

MSG:	Gas-Shielded Metal-Arc (German: Metall-Schutzgas)	NTC:	Negative Temperature Coefficient
MSI:	Medium-Scale Integration	NTE:	Not To Exceed
MSI:	Multi-Spark Ignition	NVH:	Noise Vibration Harshness
MSR:	Engine Drag-Torque Control (German: Motorschlepp- momentregelung)	NYCC:	New York City Cycle
MT:	Manual Transmission		
MTBE:	Methyl Tertiary Butyl Ether	O:	
MTTF:	Mean Time To Failure	OAT:	Organic Acid Technology
MW:	Medium Waves (German: Mittelwellen)	OBD:	On-Board Diagnostics
		OC:	Occupant Classification
		OD:	Operating Data
		ODB:	Offset Deformable Barrier Crash
N:		OEM:	Original Equipment Manufacturer
NAFTA:	North American Free Trade Agreement	OHC:	Overhead Camshaft
NAO:	Non Asbestos Organics	OHV:	Overhead Valves
NBR:	Nitrile Butadiene Rubber	OLED:	Organic Light Emitting Diode
NCAP:	New Car Assessment Program	OME:	Oxymethylene Ethers
NCS:	Needle Closing Sensor	OMM:	Surface Micromechanics (German: Oberflächen- mikromechanik)
NDIR:	Non-Dispersive Infrared (analyzer)	OP:	Operational Amplifier (German: Operationsver- stärker)
NDUV:	Nicht-Dispersive Ultraviolet (analyzer)	OPNV:	Local Public Transport (German: Öffentlicher Personennahverkehr)
NF:	Non-Ferrous	OPV:	Operational Amplifier (German: Operationsver- stärker)
NEDC:	New European Driving Cycle	OS:	Operating System
NEV:	New Energy Vehicle	OSEK:	Open Systems and their Interfaces for Electronics in Motor Vehicles
Nfz:	Commercial Vehicle (German: Nutzfahrzeug)	OSI:	Open Systems Interconnection
NHD:	Nitriding Hardness Depth	OTDC:	Overlap TDC (top dead center in the exhaust cycle)
NHTSA:	National Highway Traffic Safety Administration	OTX:	Open Test Sequence Exchange Format
NIC:	Network Interface-Controller		
NiMH:	Nickel-Metal-Hydride	P:	
NIR:	Near-Infrared	PA:	Polyamide
NIT:	Network Idle Time	PAO:	Poly- α -olefin
Nkw:	Commercial Vehicles (German: Nutzkraftwagen)	PAR:	Parity
NLGI:	National Lubricating Grease Institute	PAS:	Peripheral Acceleration Sensor
NMHC:	Non-Methane Hydrocarbon	PAX:	Pneu Accrochage, X = synonym for Michelin radial tire technology
Nht:	Nitriding Depth (German: Nitrierhärte tiefe)		
NML:	Nonmagnetic Layer		
NMOG:	Non-Methane Organic Gases		
NMOS:	N-channel MOS Transistor		
NR:	Natural Rubber		
NRZ:	Non Return to Zero		
NSC:	NO _x Storage Catalyst		
NSM:	Shunt-Wound Machine (German: Nebenschluss- maschine)		

PBT:	Polybutylene Terephthalate	PS:	Polystyrene
PC:	Passenger Car	PSD:	Power Spectral Density
PC:	Personal Computer	PSI:	Peripheral Sensor Interface
PC:	Polycarbonate	PSM:	Passive Safety Manager
PCB:	Printed Circuit Board	PSOC:	Partial State of Charge
PCM:	Phase Change Memory	PSRR:	Power-Supply Rejection Ratio
PCP:	Pre-Crash Positioning	PTB:	Physikalisch-Technische Bundesanstalt
PCV:	Positive Crankcase Ventilation	PTC:	Positive Temperature Coefficient
PCW:	Predictive Collision Warning	PTFE:	Polytetrafluoroethylene (Teflon)
PDE:	Unit injector System (German: Pumpe-Düse-Einheit)	PU:	Polyurethane
PDP:	Positive Displacement Pump	PUR:	Polyurethane
PDU:	Protocol Data Unit	PVB:	Polyvinyl Butyral
PE:	Polyethylene	PVC:	Polyvinyl Chloride
PEBS:	Predictive Emergency Braking System	PVD:	Physical Vapor Deposition
PEEK:	Polyetheretherketone	PVDF:	Polyvinylidene Fluoride
PEM:	Polymer Electrolyte Membrane	PVE:	Production Vehicle Evaluation
PEMS:	Portable Emission Measurement System	PWM:	Pulse-Width Modulation
PES:	Poly-Ellipsoid System (headlamp)	PZEV:	Partial Zero-Emission Vehicle
PET:	Polyethylene Terephthalate	PZT:	Plumbum Zirconate Titanate
PF:	Phenol Formaldehyde		
PFA:	Perfluoroalkoxy (polymers)	Q:	
pH:	Potential Hydrogenii	QFD:	Quality Function Deployment
PHEV:	Plug-in Hybrid Electric Vehicle	QM:	Quality Management
PHV:	Plug-in Hybrid Electric Vehicle	QVGA:	Quarter Video Graphics Array
PK:	Profile Code (German: Profilkurzzeichen)		
Pkw:	Passenger Car (German: Personenkraftwagen)		
PL:	Pinned Layer	R:	
PLD:	Unit Pump System (German: Pumpe-Leitung-Düse)	RA:	Rear Axle
PLL:	Phase-Locked Loop	Radar:	Radio Detection and Ranging
PM:	Particulate Matter	RAM:	Random Access Memory
PMD:	Paramagnetic Detector	RAMSIS:	Computer-aided anthropological-mathematical system for passenger simulation (German: Rechnerunterstütztes anthropologisch-mathematisches System zur Insassensimulation)
PMD:	Photonic Mixing Device	RDE:	Real Driving Emissions
PMM:	Polymethylmethacrylate	RDKS:	Tire-Pressure Monitoring System (German: Reifen-druckkontrollsystem)
PMMA:	Polymethylmethacrylate	RDS:	Radio Data System
PMOS:	P-channel MOS Transistor	RF:	Radio Frequency
PN:	Particle Number	RFA:	X-ray Fluorescence Analysis (German: Röntgenfluoreszenzanalyse)
PNLT:	Post New Long Term	RGM:	Reliability-Growth Management
POF:	Polymer Optical Fibers		
POI:	Points of Interest		
POM:	Polyoximethylene		
PP:	Polypropylene		
PPA:	Polyphtalamide		
PPNLT:	Post Post New Long Term		
PPS:	Polyphenylene Sulfide		
PPS:	Peripheral Pressure Sensor		
PROM:	Programmable Read Only Memory		

RIM:	Reaction-Injection Moulding	SENT:	Single Edge Nibble Transmission
RISC:	Reduced Instruction-Set Computing	SEW:	Steel and Iron Material Specification Sheets (German: Stahl-Eisen-Werkstoffblätter)
RME:	Rapeseed Methyl Ester (alternative fuel)	SFTP:	Supplemental Federal Test Procedure
RMF:	Rollover Mitigation Functions	SG:	Float-Angle Gradient
RMQ:	Root Mean Quad	SHD:	Surface Hardness Depth
RMS:	Root Mean Square	SHED:	Sealed Housing for Evaporative Determination
RMV:	Rollover Mitigation Function	SHF:	Super High Frequency
ROM:	Read Only Memory	SI:	Système International (International System of Units)
ROV:	Rotating High-Voltage Distribution (German: Rotierende Hochspannungsverteilung)	SI:	Speed Index, speed symbol (tires)
RON:	Research Octane Number	SiL:	Software in the Loop
RR:	Rolling Resistance	SIL:	Safety Integrity Level
RREG:	Council Directive of the European Community (today: European Union)	SIR:	Styrene-Isoprene Rubber
RRIM:	Reinforced Reaction-Injection Moulding	SIS:	Service Information System
RSM:	Series-Wound Machine (German: Reihenschlussmaschine)	SL:	Select-Low (ABS)
RTA:	Real Time Architect	SLADR:	Slave Address
RTE:	Run-Time Environment	SLC:	Sensor-Less Control
RUV:	Stationary Voltage Distribution (German: Ruhende Spannungsverteilung)	SLI:	Starting, Lighting, Ignition
RW:	Rear Wheel	SM:	Synchronous Machine
RWAL:	Rear Wheel Anti Lock Brake System	SMD:	Surface-Mounted Device
S:		SMK:	Inertia Weight Class (German: Schwungmassenklasse)
SAE:	Society of Automotive Engineers	SMPS:	Scanning Mobility Particle Sizer
SAF:	Synthetic Antiferromagnetic Free Layer	SMT:	Surface-Mount Technology
SBC:	Sensotronic Brake Control	SOC:	State of Charge (battery)
SBI:	Suppression of Background Illumination	SOF:	State of Function (battery performance)
SBR:	Styrene Butadiene Rubber	SOH:	State of Health (battery)
SC:	System Control	SPC:	Statistical Process Control
SCM:	Secondary Collision Mitigation	SPI:	Serial Peripheral Interface
SCR:	Selective Catalytic Reduction	SPICE:	Software Process Improvement and Capability Determination
SCU:	Sensor Control Unit	SR:	Slew Rate
SD:	Secure Digital	SRET:	Scanning Reference-Electrode Techniques
SD:	System Document	SRM:	Switched Reluctance Machine
SDARS:	Satellite Digital Audio Radio Service	SRR:	Short-Range Radar
SEI:	Software Engineering Institute	SSI:	Small-Scale Integration
SEL:	Sound Exposure Level	STEP:	Standard for the Exchange of Product Model Data
		STN LCD:	Super Twisted Nematic Liquid Crystal Display
		StVZO:	German road traffic licensing regulations (Straßenverkehrs-Zulassungsordnung)

SULEV: Super Ultra-Low-Emission Vehicle
SUV: Sport Utility Vehicle
SV: Changeover Valve
SVM: Space Vector Modulation
SVPWM: Space Vector Pulse Width Modulation
SWC: Software Component
SWR: Serial Wire Ring

T:

TA: Type Approval
TC: Transient Cycle
TCM: Trailer Control Module
TCP: Transmission Control Protocol
TD: Torque Demand
TDC: Time to Digital Converter
TDC: Top Dead Center (piston of internal-combustion engine)
TDMA: Time Division Multiplex Access
TEM: Transversal Electromagnetic
TFT: Thin-Film Transistor
THC: Total Hydrocarbons
TKU: Technical customer documents (German: Technische Kundenunterlagen)
TLEV: Transitional Low-Emission Vehicle
TMC: Traffic Message Channel
TMR: Tunnel-Magnetoresistive Effect
TN LCD: Twisted Nematic Liquid Crystal Display
TOF: Time of Flight
TP: Triple Point
TPA: Thermoplastic Copolyamides
TPC: Thermoplastic Copolyester Elastomers
TPE: Thermoplastic Elastomers
TPO: Thermoplastic Elastomers on an Olefin basis
TPU: Thermoplastic Elastomers on a Urethane Basis
TPV: Cross-linked thermoplastic elastomers on an olefin basis
TPEG: Transport Protocol Experts Group
TPMS: Tire Pressure Monitoring System
TRX: Tension Répartition (distributed tension)
TS: Technical Specification
TS: Torque Structure

TSG: Single-Pane Toughened Safety Glass
TSM: Trailer Sway Mitigation
TSS: Transmission Start Sequence
TTB: Time To Brake
TTC: Time To Collision
TTCAN: Time Triggered CAN
TTL: Transistor-Transistor Logic (Bipolar integrated digital circuit)
TTS: Time To Steer
TV: Television
TWC: Three-way Catalytic Converter

U:

UDC: Urban Driving Cycle
UDDS: Urban Dynamometer Driving Schedule
UFOME: Used Frying Oil Methyl Ester
UHF: Ultra-High Frequency
UIS: Unit Injector System
UL: Upper Limit
ULEV: Ultra-Low-Emission Vehicle
ULSD: Ultra Low Sulfur Diesel
ULSI: Ultra Large Scale Integration
UMTS: Universal Mobile Telecommunication System
UN: United Nations
UNECE: United Nations Economic Commission for Europe
UPS: Unit Pump System (Pump-Line Nozzle)
UPS: Ultraviolet Photo Spectroscopy
USA: United States of America
UTP: Unshielded Twisted Pair
UV: Ultraviolet
UWB: Ultra Wide Band

V:

V2V: Vehicle to Vehicle
V2X: Vehicle to Infrastructure
VA: Front Axle
VCI: Volatile Corrosion Inhibitor
VCO: Voltage-Controlled Oscillator
VCR: Variable Compression Ratio
VDA: German Association of the Automotive Industry (German: Verband der Automobilindustrie)

VDA-FS: German Association of the Automotive Industry – Surface Data Interface (German: Verband der Automobilindustrie – Flächenschnittstelle)

VDE: Association for Electrical, Electronic and Information Technologies (German: Verband der Elektrotechnik Elektronik Informationstechnik e.V.)

VDI: Association of German Engineers (German: Verein Deutscher Ingenieure)

VDM: Vehicle Dynamics Management

VDU: Vehicle Dynamics Unit

VDX: Vehicle Distributed Executive

VE: Distributor Injection Pump (German: Verteilereinspritzpumpe)

VFB: Virtual Function Bus

VFD: Vacuum Fluorescence Design (Vacuum-fluorescence display technology)

VGA: Video Graphics Array

VHAD: Vehicle Headlamp Aiming Device (adjusters for front headlamps)

VHD: Vertical Hall Device

VHF: Very High Frequency

VLF: Very Low Frequency

VLI: Vapor Lock Index

VI: Viscosity Index

VIS: Visible

VLSI: Very Large Scale Integration

VMM: Volume Micromechanics

VOL: Visual Optical Aim Left

VOR: Visual Optical Aim Right

VPI: Vapor-Phase Inhibitor

VR: Distributor Injection Pump, Radial-Piston Pump (German: Verteilereinspritzpumpe, Radialkolbenpumpe)

VRLA: Valve-Regulated Lead-Acid

VSA: Vehicle Stability Assist

VSC: Vehicle Stability Control

VTG: Variable Turbine Geometry (exhaust-gas turbocharger)

VVT: Variable Valve Timing

W:

WdK: Economic Association of the German Rubber Industry (German: Wirtschaftsverband der deutschen Kautschukindustrie)

WEC: World Endurance Championship

WERBP: wet Equilibrium Reflux Boiling Point

WHSC: World Harmonized Stationary Cycle

WHTC: World Harmonized Transient Cycle

WLAN: Wireless Local Area Network

WLTC: Worldwide Harmonized Light Vehicle Test Cycle

WLTP: Worldwide Harmonized Light Vehicle Test Procedure

WMTC: Worldwide Motorcycle Test Cycle

WNTE: Worldwide Harmonized Not To Exceed

WRC: World Rally Championship

WWH: Worldwide Harmonized

WWW: World Wide Web

X:

XML: Extensible Markup Language

XPS: X-ray Photoelectron Spectroscopy

Z:

ZEV: Zero-Emission Vehicle

ZME: Metering unit (German: Zumesseinheit)

Symbols:

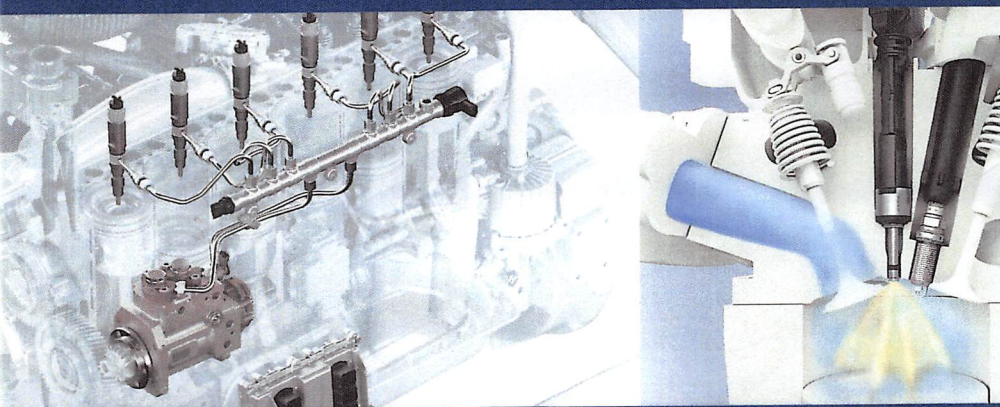
3PMSF: Three Peak Mountain Snow Flake (snow-flake symbol)

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